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DENSIFICATION OF REFUSE-DERIVED FUELS: PREPARATION, PROPERTIES AND SYSTEMS FOR SMALL COMMUNITIES

by

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Grant No. 804150

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This report covers an investigation of the operation, performance and product characteristics of a waste shredding and densification subsystem for production of d-RDF from air-classified light fraction and provides a technical and economic evaluation of d-RDF facilities for small communities.

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

One of the newer approaches to the processing and utilization of municipal solid waste is the production of densified refuse-derived fuels for burning as a supplement to coal in industrial and institutional stoker-type boilers. This publication reports on the first comprehensive investigation of the preparation, properties and economics of densified refuse-derived fuel. Along with the separate report on the results of the combustion tests (conducted under Contract 68-03-2426 by the Environmental Protection Agency), a great deal of experimental data and operational experience are available to potential users considering implementation of this concept.

Francis T. Mayo, Director
Municipal Environmental
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ABSTRACT

Densified refuse-derived fuel (d-RDF) is produced by compacting refuse-derived fuel (RDF) into agglomerated pieces sufficiently cohesive to sustain storage and handling. The use of this d-RDF product as a substitute for coal in spreader-stoker boilers is a developing resource recovery alternative.

This report covers an investigation of the operation, performance and product characteristics of a waste shredding and densification subsystem for production of d-RDF from air-classified light fraction and provides a technical and economic evaluation of d-RDF facilities for small communities.

During the investigation, a pellet mill was used to produce nearly 1300 Mg of pellets that were later test burned. Treated in this report are the performance and effects of modification of the feed preparation equipment, particularly the secondary shredder. Discussion of the densifier operation and maintenance centers on the impact of feedstock properties, feedrate control, equipment configuration and equipment wear on pellet production and properties. Physical properties of pellet samples analyzed over 1300 Mg production period are summarized. Observations on handling and storage are discussed with recommendations made as to how potential problems might be minimized.

The approach taken in the evaluation of d-RDF facilities for small communities is to derive the affordable cost, on a break-even basis, for the plant and equipment needed to produce a RDF feedstock from a densification module. The analysis uses projections for the capital, operating and maintenance costs of densifying.

This report was submitted in fulfillment of Grant No. 804150 by the National Center for Resource Recovery, Inc., under sponsorship of the U.S. Environmental Protection Agency. It covers the period September 1975 to March 1979.

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Many companies lent their equipment for the investigations or donated their time and assistance. We thank California Pellet Mill, particularly Robert McDaniel and Bruce Young (pellet mill), Triple/S Dynamics (air classifier, screen and knife shredder tests), and the Heil Company and Newell-Dunford, Ltd. (secondary shredder).

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SECTION 1

INTRODUCTION

BACKGROUND

The growing emphasis on energy recovery from municipal solid waste has led to the development of several chemical and mechanical processes for producing various forms of refuse-derived fuel (RDF). The RDF may be burned alone or in combination with fossil fuels for heat recovery and/or power generation. The production of a densified refuse-derived fuel (d-RDF) as a substitute for coal in industrial or institutional spreader-stoker boilers is a developing alternative for resource recovery.

The original and most commercialized application of RDF is the suspension firing of a fluff RDF with pulverized coal in utility boilers. Typically, these boilers are large (more than 25 kg/s (200,000 lb/h) steam), and the RDF requirements can be 1,000 Mg (1,100 tons) or more per day - a condition which requires extensive modifications to the boiler storage and feed systems.

The potential market for RDF as a supplemental fuel, however, is not limited to these large boilers. Smaller industrial and institutional stoker-fired boilers, in the range of 11,000 to 90,000 kg (25,000 to 200,000 lb) of steam per hour, offer an alternative. Because of their lower fuel requirements, higher fuel costs, and greater number of installations, the stoker-fired boilers are particularly attractive for smaller communities. To maintain storage and feed system capacities and to assure proper distribution and burning on the grates, an RDF product with a comparable range of properties to conventional stoker (particle) coal is necessary. Rather than a low density fluff RDF, a densified* form of refuse-derived fuel (d-RDF) would be most suitable.

---

*The term "densified" is used as a generic description rather than specific adjectives such as "pelletized" or "cubetted." Obviously, these terms describe specific products, all of which fall into the category of "densified." The generic term, "densified refuse-derived fuel" and its abbreviation "d-RDF" were first proposed by Harvey Alter in May 1975 in the proposal for the work described here.

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Modifications to a stoker boiler to burn d-RDF are expected, in most cases, to be small. Interest in using d-RDF as a commercial fuel is greatly enhanced by the fact that it is much more easily stored and transported than a fluff product.

There have been increasing numbers of trials in production and combustion of d-RDF over the last decade; however, the technology of densification began in 1880 with the issue of the first U.S. patent for densifying sawdust for fuel [1]. It describes heating sawdust or other wood residues to 150°F and compacting to the "density of bituminous coal" (specific gravity 1.25) in a strong mold with a steam hammer. Other early patents describe the various forms of densifiers (pelletizers, briquetters, cubetters and extruders) mainly in agricultural applications.

It was not until the work of Stirrup in 1959 and Hollander in 1971 that the interest in using densified waste as a fuel developed; both men were clearly ahead of their time [2,3]. Appendix A provides a representative summary of U.S. facilities and manufacturers of equipment or systems for producing d-RDF from municipal solid waste (MSW). Experience in producing (and test firing) d-RDF is also increasing in Europe. Discussions of some of these efforts have been reported [4,5,6,7].

The test in Fort Wayne provided the first reported results of d-RDF combustion in the U.S. Growing interest since then is apparent from the summary of d-RDF test burns listed in Appendix A [3].

The concept of RDF and d-RDF can be extended to other waste-derived or biomass fuels [8]. Although d-RDF is generally a fuel for stoker boilers analogous to lump coal, evaluations have also been made of re-grinding d-RDF for use in pulverized coal-fired boilers [9].

In response to interest in using some form of RDF in other boilers, the Municipal Environmental Research Laboratory of the U.S. Environmental Protection Agency (EPA) implemented a program to investigate the feasibility of technically, environmentally, and economically producing and burning d-RDF.

The objectives of the program were to:

(1) investigate the theoretical aspects and relevant material and equipment parameters involved in densification of RDF;

(2) study the production and physical properties of d-RDF, and project the economics for a d-RDF system in a small community;

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(3) produce d-RDF for large-scale combustion tests; and

(4) establish the combustion characteristics of d-RDF and the effects of boiler performance, emissions and other factors associated with its use.

The University of California at Berkeley received a research grant for work on the theoretical aspects of densification [10]. The activity, related to boiler testing, is being accomplished under an EPA contract with Systems Technology Corp. [11]. Study of the preparation, properties and economics of d-RDF and production of d-RDF for testing* accomplished by the National Center for Resource Recovery (NCRR), is the subject of this report.

SCOPE AND OBJECTIVES

For about 2-1/2 years, NCRR processed MSW into d-RDF on a pilot scale at its Equipment Test and Evaluation Facility (ETEF). The d-RDF production employed two different process flows. About 270 Mg (300 tons) of pellets were produced between fall 1976 and spring 1977. Following changes in key equipment, 1,000 Mg (1,100 tons) more was produced between fall 1977 and fall 1978. Most of the d-RDF was in the form of pellets 13 mm (1/2 in.) in diameter; 90 Mg (99 tons) were pellets 25 mm (1 in.) in diameter.

The objective of the experimental work was to investigate and report on the operation, performance and production characteristics of a shredder and densifier subsystem designed to produce d-RDF from shredded air-classified, light fraction.

ORGANIZATION OF THE REPORT

The first five sections of this report cover the approach and findings on feed preparation, densification, d-RDF properties, handling and storage. The last three sections provide an evaluation of d-RDF systems for small communities in the form of a concept design, alternative layouts, and economic analysis of a d-RDF facility for a small community.

Some of the information in the report has been previously published, either in open literature or in special reports from the National Center. Publications resulting from this grant are included in Appendix B.

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*Teledyne National Corp. provided 1,350 Mg (1,487 tons) of additional d-RDF from its Cockeysville, Md. resource recovery facility for the test firing in Erie, PA.

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FACILITY

The work described in this report was conducted at the National Center's Equipment Test and Evaluation Facility, located in what was the oversize, bulky waste-processing area of the District of Columbia's Solid Waste Reduction Unit No. 1, a large, operating incinerator. ETEF was operational from 1974 to June 1979. Packer trucks were diverted from the incinerator tipping floor to provide feedstock for investigations. Unrecovered materials, or samples after use, were disposed of in the incinerator pit.

The oversize, bulky waste-processing area originally consisted of a tipping floor and steel pan conveyors feeding a 750 kW (1,000 hp) horizontal hammermill. The output of the hammermill dropped onto a vibrating pan conveyor, then to a rubber belt conveyor, which carried it past a drum magnet. The nonmagnetic portion was then conveyed to the incinerator pit. The District of Columbia permitted temporary modifications to the facility so that it could be converted into a pilot plant for resource recovery investigations.

The capacity of the shredder is probably of the order of 90 Mg/h (100 tons/h). However, the infeed and outfeed conveyors installed were intended for a higher bulk density than packer truck refuse. Consequently, the capacity of the system with packer truck refuse was no more than about 20 Mg/h (22 tons/h).

The modifications allowed for the installation of many different unit operations for fuel processing and material recovery. In most instances, however, there was a severe space restriction, and equipment had to be installed and located in areas and configurations that were far from adequate.

Only compactor truck refuse collected in residential neighborhoods was used for the work described in this report.

There have been previous reports describing the process flow and equipment at ETEF [12,13]. The description below omits that portion of the facility which was used for processing the heavy fraction to recover metals and glass [14,15].

Process Flow

Figures 1 and 2 are schematics of the equipment configurations from fall 1976 to spring 1977 (Configuration 1) and from fall 1977 through fall 1978 (Configuration 2) production periods. Table 1 describes this equipment.

The refuse was first size-reduced in the primary shredder. In Configuration 2, a vibratory feeder was added to feed the air

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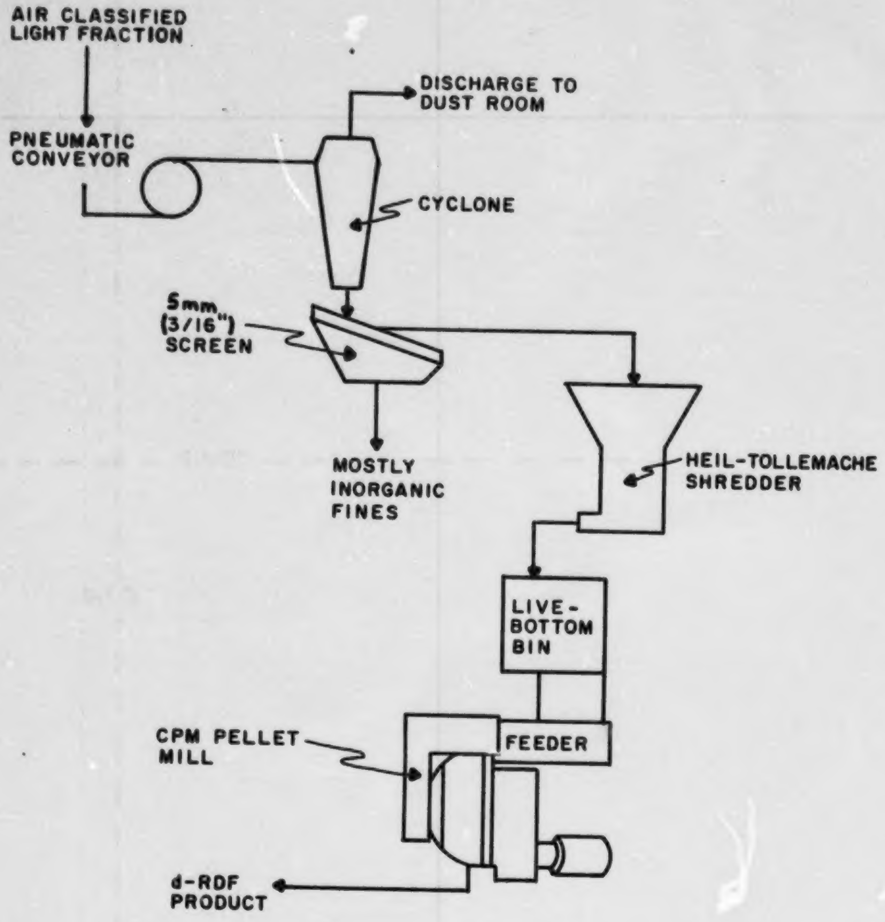
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DISCHARGE TO DUST ROOM
PNEUMATIC CONVEYOR
CYCLONE
5mm (3/16") SCREEN
MOSTLY INORGANIC FINES
HEIL-TOLLEMACHE SHREDDER
LIVE-BOTTOM BIN
CPM PELLET MILL
FEEDER
d-RDF PRODUCT

Figure 1. Portion of Equipment Test and Evaluation Facility for preparation of d-RDF, configuration 1.

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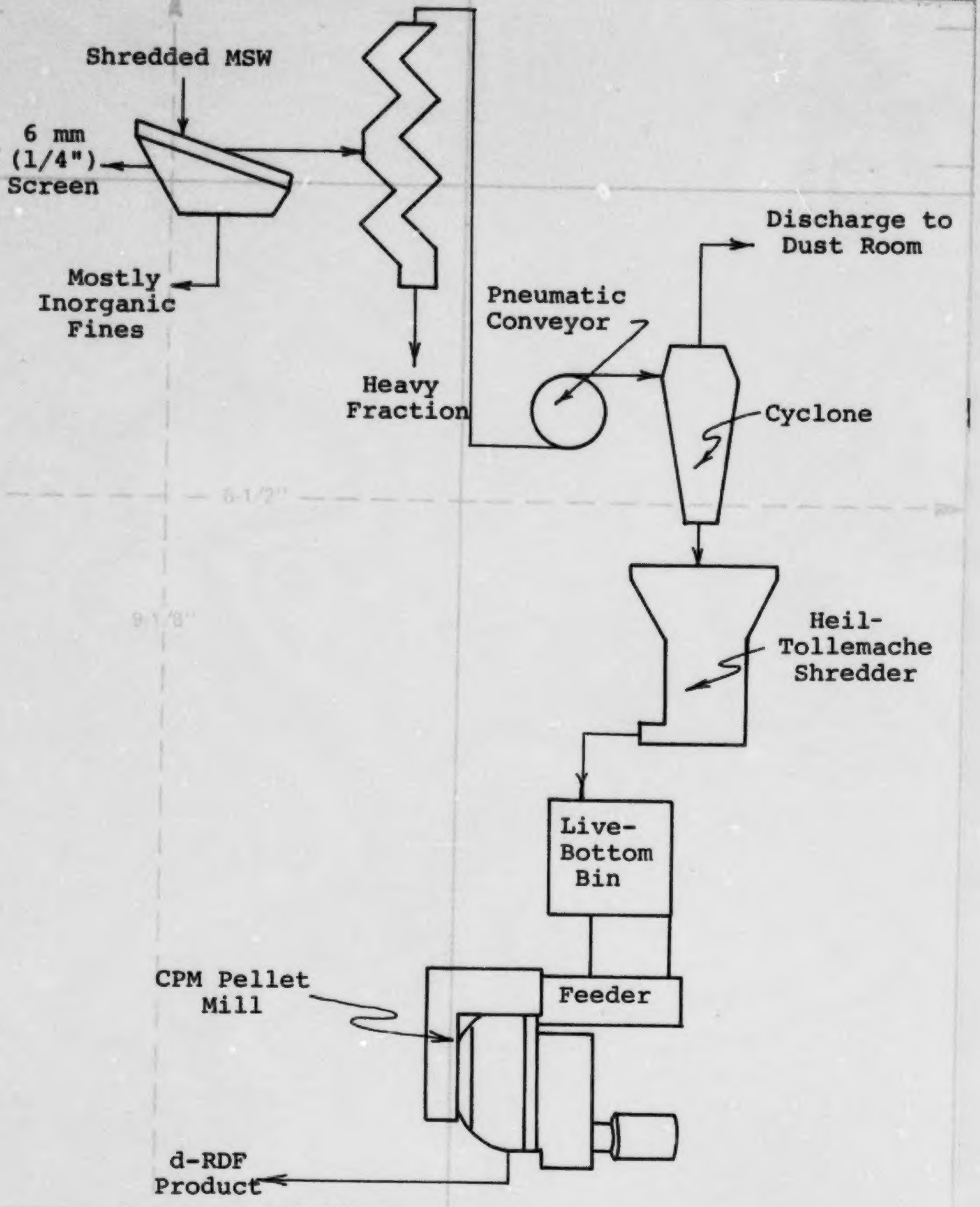
Shredded MSW
6 mm (1/4") Screen
Mostly Inorganic Fines
Heavy Fraction
Discharge to Dust Room
Pneumatic Conveyor
Cyclone
Heil-Tollemache Shredder
Live-Bottom Bin
Feeder
CPM Pellet Mill
d-RDF Product

Figure 2. Portion of Equipment Test and Evaluation Facility for preparation of d-RDF, configuration 2.

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TABLE 1. DESCRIPTION OF ETEF d-RDF PREPARATION EQUIPMENT

	Item	Manufacturer - model	Source	HP - Description
1.	Primary Shredder	Williams Patent Crusher Co. Model 780	D.C. Gov't.	745 kW (1,000 hp) horizontal hammermill, 24 104 kg (230 lb) hammers, grates 23 x 30 cm (9 x 12 in.), 720 rpm (no load)
2.	Screen Feeder	Triple/S Dynamics Texas Shaker (with ball tray)	Manufacturer loan	2.1 x 6.1 m (7 x 20 ft), 7.5 kW (10 hp), 6 mm (1/4 in.) punched plate on 11 mm (7/16 in.) staggered centers.
3.	Air Classifier	NCRR - Research Unit	NCRR built	6.1 m (20 ft) high x 2.1 m (7 ft) wide x 41 cm (16 in.) deep with baffles; 93 kW (125 hp) fan for 570 m^3/min (18,000 CFM) nominal flow
4.	Cyclone	Fisher-Klosterman Model XQ52 plus Carter-Day Rotary Valve Model AN-24	Purchased	8.2 m (27 ft) high, 2.6 m (8-1/2 ft) long x 1.8 m (6 ft) diameter barrel. De-entrainment box 1.5 m x 1.2 m x 1.2 m (5 ft x 4 ft x 4 ft) with 61 cm (24 in.) diameter outlet. Rotary valve is 56 cm (22 in.) diameter, 1.5 kW (2 hp)
5.	Pneumatic Transport System	Nadustco Fan and Cyclone	Purchased/ NCRR built	283 m^3/min (10,000 CFM) fan, 45 kW (60 hp) positive pressure, 36 cm (14 in.) square duct
6.	Secondary Shredder	Heil Model 42 D	Manufacturer loan	vertical shaft, modified with stators, 112 kW (150 hp)
7.	Live-bottom Feeder	California Pellet Mill	Lease	1.3 m (52 in.) long x 1.3 m (52 in.) wide x 0.91 m (36 in.) high, 4 screws, 5.6 kW (7-1/2 hp), vari-speed
8.	Densifier	California Pellet Mill Model 8162-B1	Lease	76 cm (30 in.) I.D. die, 13 mm (1/2 in.) holes, 170 rpm, 112 kW (150 hp); 25 cm (10 in.) and 33 cm (13 in.) O.D. corrugated rolls; 5.6 kW (7-1/2 hp) Even Flow feeder and 112 kW (15 hp) mixer screws

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classifier. A screen deck was added to the feeder to remove fine particulate material (later shown to be mostly inorganic) as a means of investigating the upgrading of the fuel product. Several different air classifiers were investigated, as referenced and described later in the text [15].

The light fraction from the air classifier was de-entrained in a cyclone, reintroduced through a rotary air lock into a pneumatic conveyor and then discharged onto the 5 mm (3/16 in.) screen (Configuration 1) or into the Heil-Tollemache shredder (Configuration 2).

The 5 mm (3/16 in.) screen was employed to investigate the removal of fine particulate matter from the light fraction. The dust and air effluent from the cyclone were discharged into a large settling chamber.

After the Heil-Tollemache shredder further reduced the light fraction, it was conveyed to the live-bottom bin. The live-bottom bin served to control surges and meter the material through two screw feeders to the densifier. The densifier product was discharged by conveyor to a 15 m^3 (20 yd^3) container or a 10 m^3 (14 yd^3) dump truck for transport to storage. The densifier and its auxiliary apparatus are described in detail in Section 3.

In reviewing this report, it is important to remember that ETEF was a pilot plant. Although it resembled what might be utilized as a full-scale plant, it was assembled rather than engineered to accommodate to an existing, constrained space. Although the densification equipment was at or near full scale, capacity and surge characteristics associated with the feed preparation system had significant influence on operations and densifier products. For this reason, care should be taken in extrapolating the experiences at ETEF to engineered, full-scale applications.

Table 1 indicates equipment which was provided on-loan by various manufacturers. Their contributions are gratefully acknowledged.

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SECTION 2

FEED PREPARATION

The main functions of the feed preparation system were primary shredding, intermediate screening, air classification and secondary shredding. Particular attention will be given to secondary shredding because of the close relationship between feedstock particle size and densifier operation. Significant effort was expended in the project to properly size the feedstock and manage the wear on the shredder. The approaches and results are reported here.

6-1/2

Included first is a brief discussion of the intermediate screening and air classification processes. As will be noted, changes made in the equipment during the course of the d-RDF production had an effect on the densifier operation and d-RDF properties.

9-1/8

SCREENING

The investigations of screening and air classification were part of a concurrent EPA experimental program. While only the pertinent results of these studies are cited here, the overall results have been reported [15].

The particle size distribution of typical, primary-shredded MSW is presented in a Rosin-Rammler format in Figure 3 and further described by the Rosin-Rammler function also shown [16]. The function predicts that 30.4% of the feed is less than 6.4 mm (1/4 in.). This number was verified by later analyses of 10 samples of shredded MSW with an identical mean of 30.4%.

The significance of this fraction is that it contains primarily inorganic particulate material which is likely to "fly" with the light fraction when air-classified. These removable inorganic fines (RIF) will add to the ash, or non-combustible, portion of the fuel and lead to increased abrasion and wear on the secondary shredder and densifier. Reference 15 provides a thorough description of this RIF fraction, its predicted impact on ash, and the screening methods investigated for RIF removal.

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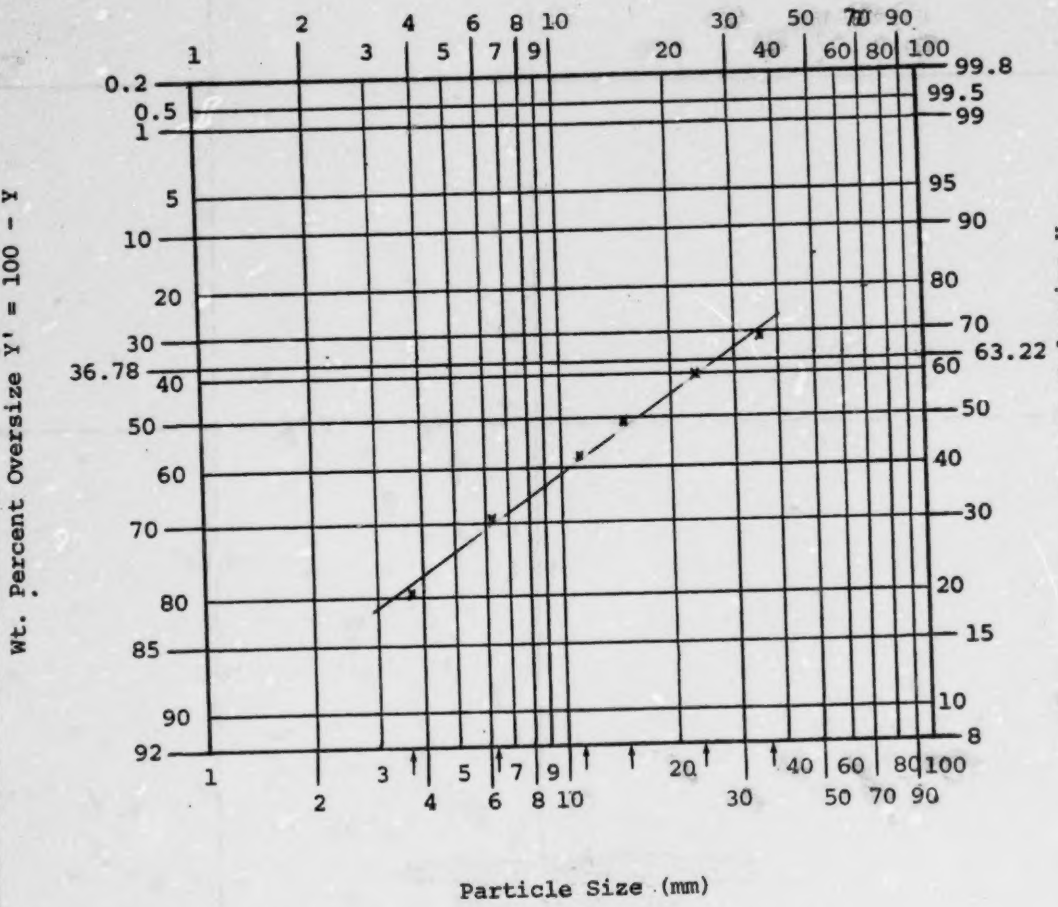

— x — Primary Shredded Waste

Expressed as a Rosin-Rammler Function:

$(1-f) = [\exp - (D/2.77 \times 10^4)^{0.689}]$

f = cumulative wt. fraction smaller than D
D = particle diameter, microns

Figure 3. Particle size distribution of primary shredded waste.

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The result of these investigations of vibratory screens on both shredded waste and air-classified, light fraction was that flat screening of MSW could not be recommended. Further, a tumbling action, such as occurs in a rotary screen (trommel), is suggested.

AIR CLASSIFICATION

During the period of pellet production at ETEF, two substantially different classifiers were employed. The first, used for the initial 270 Mg (300 tons) of production was a Triple/S Vibrolutriator^{TM} and the second used for the remaining 1,000 Mg (1,100 tons) of production was a vertical zig-zag-type classifier. As mentioned above, during the installation of the zig-zag classifier, a vibrating feeder screen was added.

The parameters measured during these investigations included separating air velocity, light/heavy split, and recovery of specific seed materials. A comparison of the two units indicated that the vertical zig-zag classifier produced a similar yield of light fraction as the Vibrolutriator^{TM} but at a reduced air velocity. This suggests that with the zig-zag classifier operated at the same yield, the carryover of RIF would be lower than with the Vibrolutriator^{TM}. As pointed out earlier, the ash content measured in the d-RDF was reduced from 26 to 22 wt%, dry basis, after the Vibrolutriator^{TM} was replaced by the vertical zig-zag classifier. However, this improvement in ash content cannot be ascribed solely to the air classifier, as the feeder screen was also added at this time and would have had the effect of lowering the ash as well.

SECONDARY SHREDDING

The primary shredded, air-classifed, light fraction must be further decreased in size prior to densification in order to reduce milling action on the material by the die and roller assemblies; otherwise, there would be increases in wear and power consumption and a decrease of pellet mill capacity. Also, smaller sized feed leads to higher bulk densities and improved flow.

The secondary shredder at ETEF was a vertical shaft, 190 kW (250 hp) reversible Heil-Tollemache hammermill. The outside walls are funnel-shaped at the top and cylindrical at the bottom. The rotor is made up of 13 discs carrying sets of hammer shafts or pins upon which the hammers are free to swing. A projection of the rotor arrangement showing the original hammer configuration is provided in Figure 4. In this figure, the "station" refers to the location of the hammers vertically, and the "shaft" to their positions around the rotor circumference. The

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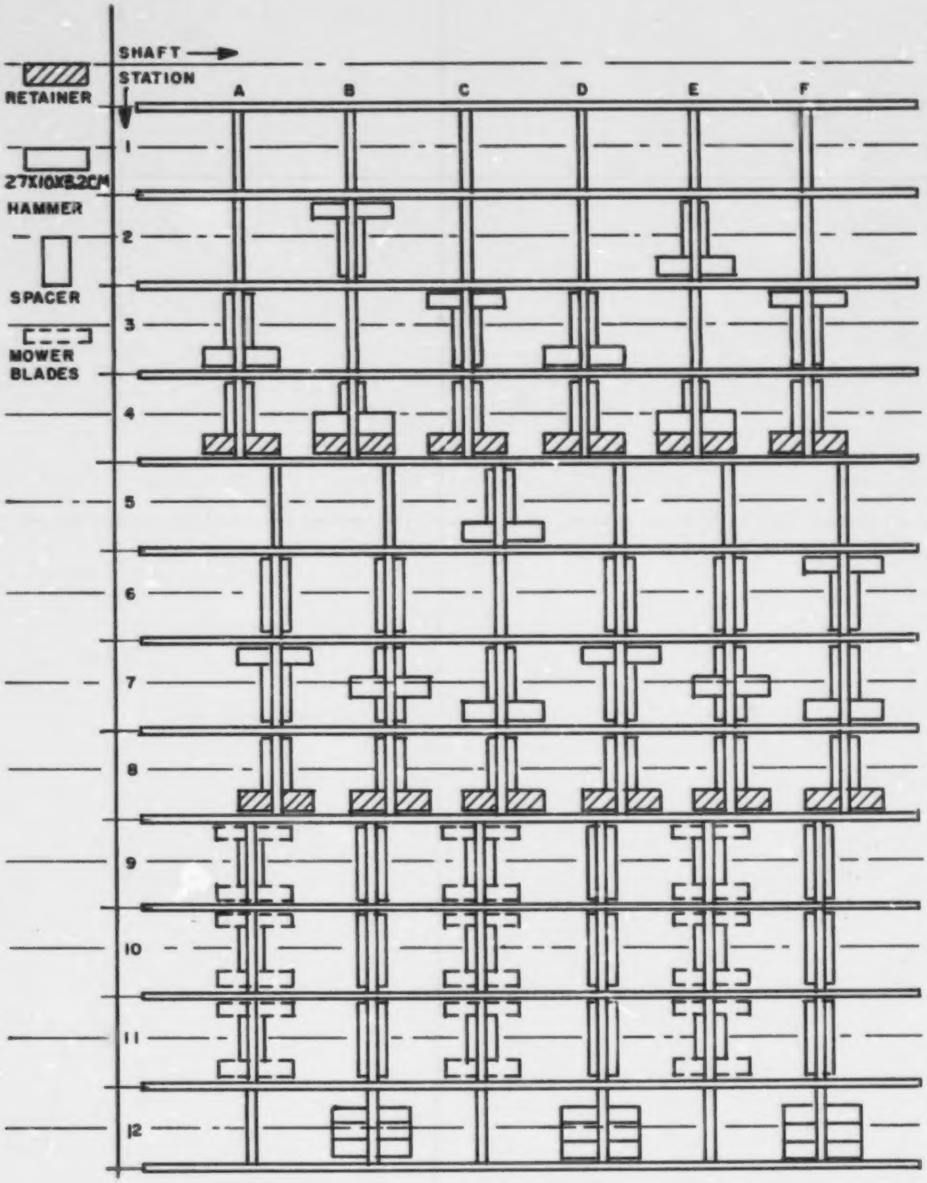
SHAFT
STATION
A
B
C
D
E
F
RETAINER
27X10X8.2CM HAMMER
SPACER
MOWER BLADES
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2
3
4
5
6
7
8
9
10
11
12

Figure 4. Original Heil hammer configuration.

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stations are grouped by general function into several sections: stations 1 to 4 make up the top or pre-break section; stations 5 to 8 the middle or throat section; stations 9 to 11 the grind section; and station 12 the sweep section. The action between the rotating hammers and stationary, raised cleats in the grind section provide for the significant size reduction.

In all other applications of the ring extrusion-type densifiers, the largest feedstock particle is smaller than the die hole diameter, however this requirement was not originally established or achieved in this program. The overriding concerns were the limitations of the shredder, and the potential problems with dust generation and material flow with too fine a product. The size thought suitable for densification without introducing excessive fines was 95% passing 25 mm (1 in.).

With no practical experience in shredding air-classified light fraction for a guide, the placement of 34 hammers shown in Figure 4 was tried. In the first operation, it was noted that while there was no difficulty in shredding the paper portion of the light fraction, the textiles, and to a lesser extent the plastics, were not reduced to the same degree. Large pieces, frequently 100 mm x 100 mm (4 in. x 4 in.), would pass through the shredder and jam between the screw flights and walls, wrap around the augers, or enter and jam the densifier.

Working with the manufacturer, a number of changes in hammer styles and configurations, and use of fixed stators were investigated as solutions to the textile problem. The criteria for judging improvements became the extent and consistency of textile size control. Before a discussion of this effort, it should be noted that other schemes to remove textiles were considered; none, however, were judged satisfactory. An attempt to drop the textiles in the heavy fraction by reducing the air velocity in the air classifier resulted in a lower yield of RDF and up to 12% of textiles still present in the light fraction. Screening approaches were also considered, but were hindered by the low bulk density (32 to 64 kg/m^3 or 2 to 4 lb/ft^3) and predominantly flake-like material in the light fraction.

The initial changes to the shredder were on hammer size and number. Eighteen thinner, knife-style hammers (10 mm (3/8 in.) thick) were installed in the grinding section in place of the nine original, thicker (32 mm (1-1/4 in.)) hammers. However, large pieces of textiles were still discharged. A series of five trials varying the number (34 up to 72) and length (to reduce clearances) of the hammers were made. A significant reduction on the particle size of the paper and plastics was observed, in one case, with up to 80% passing 13 mm (1/2 in.). Surprisingly, a corresponding improvement was still not apparent in the textile particle size with as little as 1% of the textiles passing 25 mm (1 in.).

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The most significant relative improvement resulted from the addition of fixed stator bars at various locations in the grinding section. The bars, 200 mm long x 100 mm wide x 10 mm thick (8 in. long x 4 in. wide x 3/8 in. thick), were located so that the rotating hammers on stations 9 to 11 passed between them, creating a scissors action. A view of the stators and hammers is provided in Figure 5. After being encouraged by the initial results, several more stators were added, achieving the configuration of stators and hammers shown in Figure 6. The results of the particle size analysis of the secondary shredded product for this configuration is shown in Figure 7. The particle size distribution of the air-classified light fraction is also shown for reference. These data points are averages for four samples of the primary shredded product and six samples of the secondary shredded product. The lines are drawn for reference. It was observed that while, characteristically, the textiles were larger as a whole, the textiles' distribution was relatively narrow, ranging from 25 to 65 mm (1 to 2-1/2 in.). One sample from a run in this configuration indicated even better textile size control with 42% less than 25 mm (1 in.). Although textiles in this size range can still lead to jamming, the densifier operation was judged to be significantly improved.

While hammer styles were later varied for investigation of wear, the hammer and stator configurations shown in Figure 7 were not varied over the course of some 1,300 Mg (1,440 tons) throughput. There were, however, two subsequent modifications in the pre-grind and sweep section during early operations.

The first modification resulted from observation of a ball of textiles spinning around in the upper cone portion of the shredder. At times, a clump would surge through the shredder with negligible size reduction and jam the densifier feed screws or the die. Raised bars were added along the side of the cone section to break up the vortex and cause the textiles to drop as they entered the shredder. Experience indicated this scheme to be generally effective.

A second modification reduced the area of the discharge port by 50% with the objective being to increase material residence time in the shredder, thereby reducing particle size in general and textiles in particular. As sufficient comparative data before and after the modification were not available, the effect cannot be quantified.

During the program, instrumentation was installed to measure the power consumption of the secondary shredder. However, at the low throughputs through the shredder (as limited elsewhere in the system), the variation in consumption was within 110% of the idle power, and thus too low to make any valid interpretations or extrapolations.

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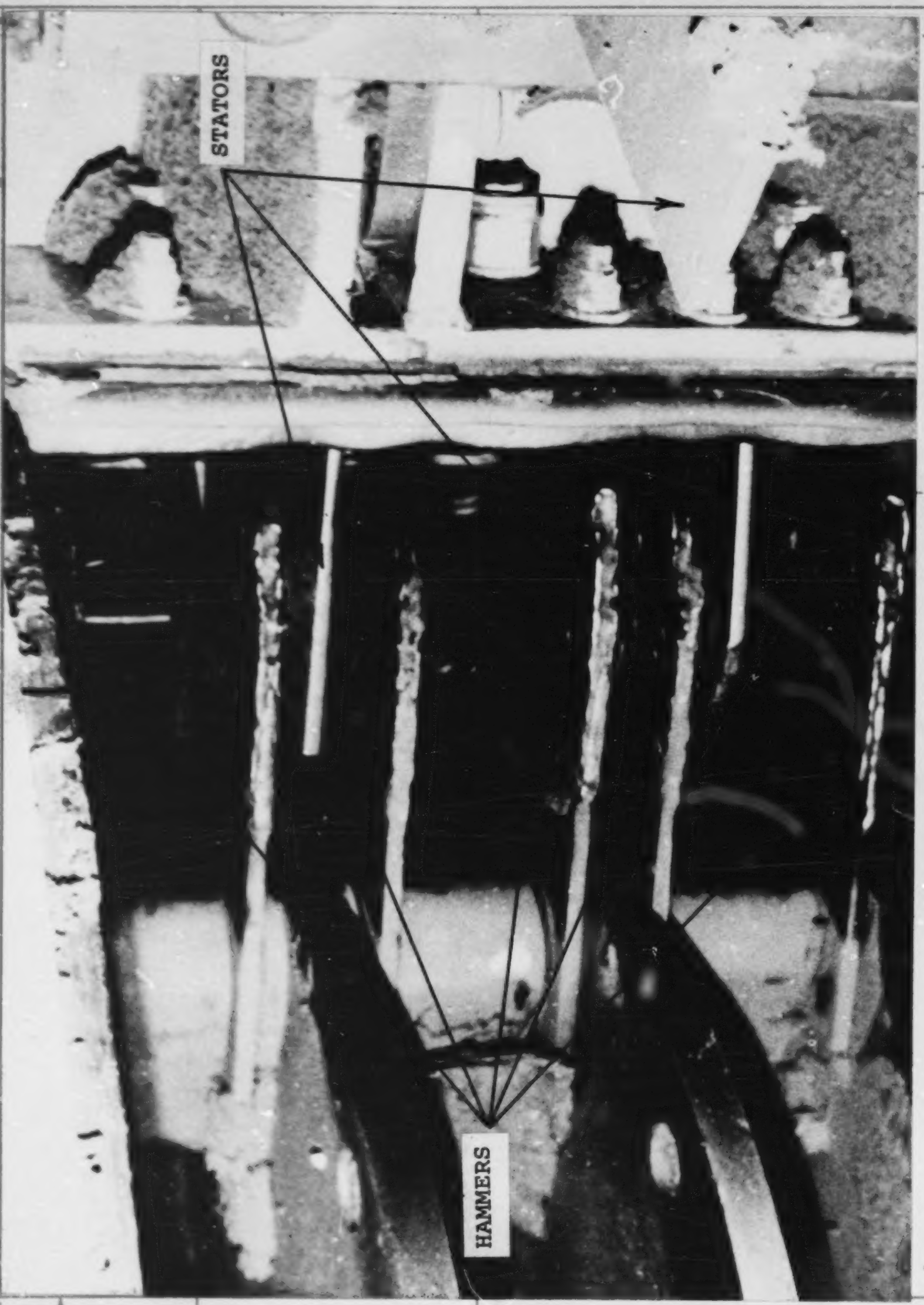
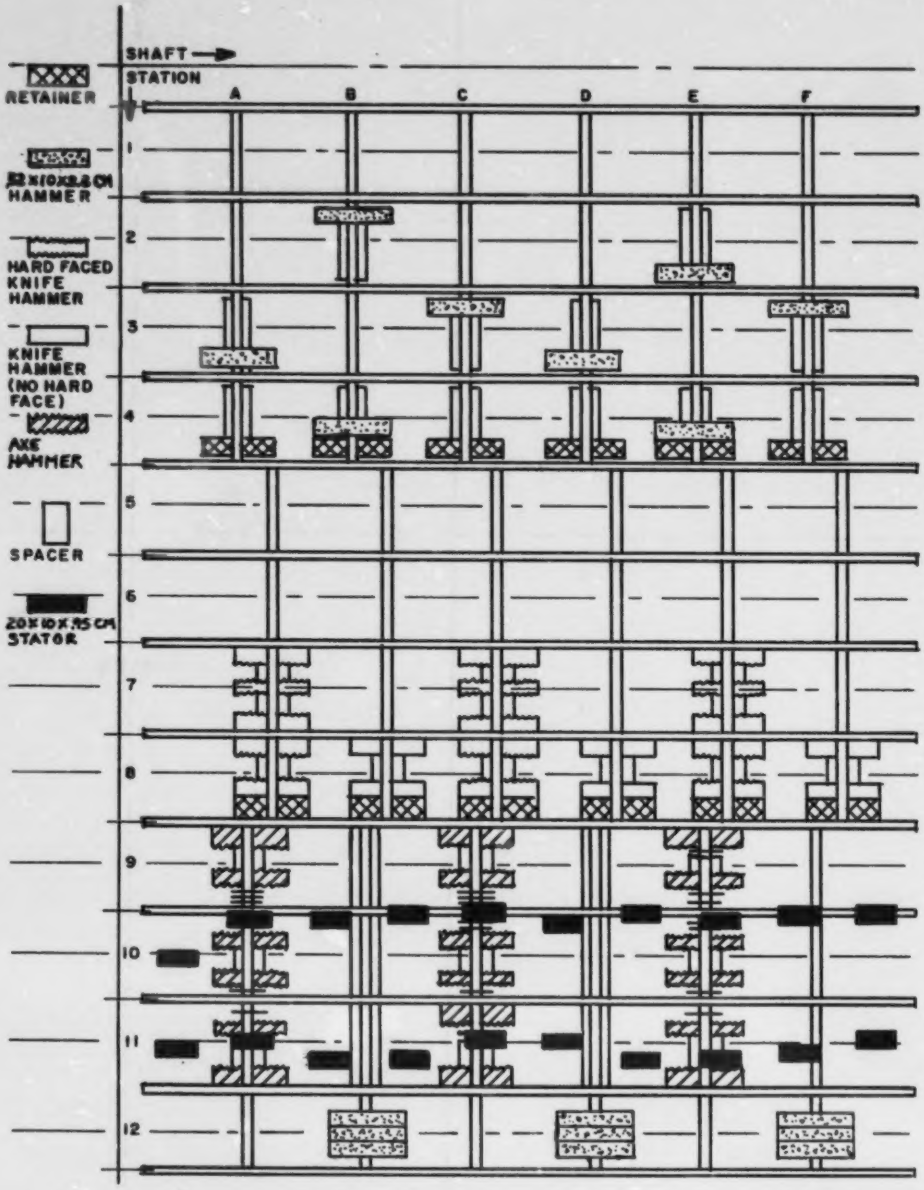


Figure 5. View of hammers and stators in grinding section.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RETAINER
22X10X2.5 CM HAMMER
HARD FACED KNIFE HAMMER
KNIFE HAMMER (NO HARD FACE)
AXE HAMMER
SPACER
20X10X.95 CM STATOR

Figure 6. Final secondary shredder hammer and stator configuration.

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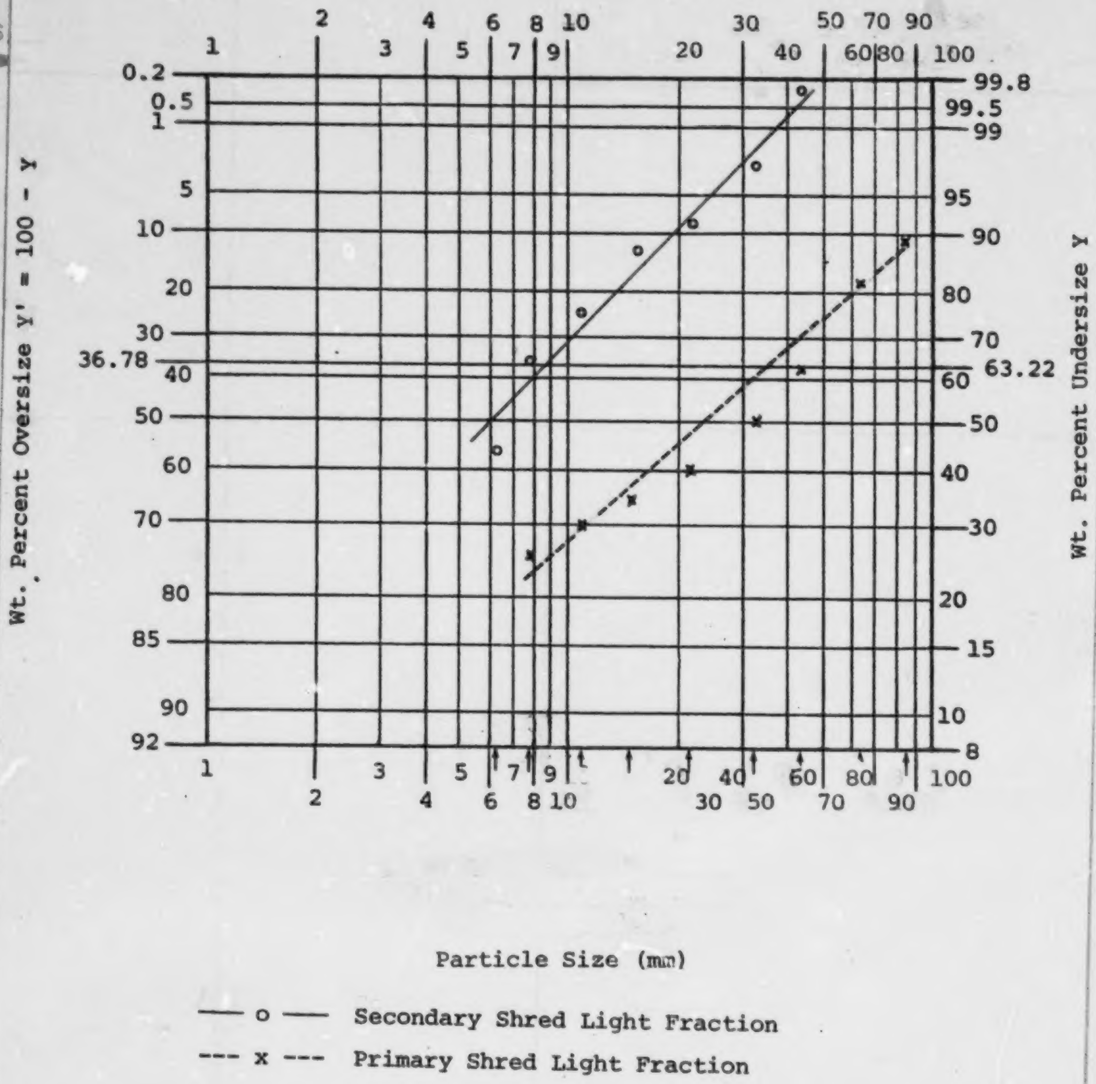

Figure 7. Particle size distribution of primary and secondary shredded light fraction.

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SHREDDER HAMMER WEAR

Hammer wear and alternate hammer types were investigated over the course of the shredding of 1,300 Mg (1,430 tons) of air-classified, light fraction. The data are reported for each of four shorter increments, namely 92 Mg (101 tons), 104 Mg (115 tons), 229 Mg (252 tons) and 546 Mg (601 tons), due to programmed or unprogrammed hammer changes.

The hammer wear by station during the longest production period of 546 Mg (601 tons) is in Table 2. Two methods of measuring the wear are specific hammer wear, or the average individual hammer weight loss per Mg of waste processed, and percentage hammer wear, or the percentage of original hammer weight lost.

Figure 8 shows the worn hammers in their relative positions as they would be in the shredder. A closer look at the three types of hammers used during this period in new and typically worn condition is provided in Figure 9. The shredder rotation was occasionally reversed to equalize wear on both edges of the hammers. Initially, the leading edges and tip were rounded and wear progressed along the top and down the side. On the knife-style hammers, the leading edge thinned out to a beveled edge as the blade wore. On the axe-type, the softer metal between the surface layers of hardfacing wore more quickly, forming cups or pockets along the leading edge. Surprisingly, stators that were not hardfaced showed only minor wear in the form of bullnosed leading edges.

In normal shredder operation, hammers were regularly hardfaced, in-place, and periodically switched between high and low wear stations to average out the wear. However, to assure measurable wear, neither periodic hardfacing nor interchanges were made during the course of these evaluations.

The highest specific hammer weight loss was at station 10 at 1.8×10^{-3} kg/Mg (3.6×10^{-3} lb/ton). Since this was in the grinding section and amidst the fixed stators, the result was not surprising. Nearly as high a specific hammer wear of 1.6×10^{-3} kg/Mg (3.3×10^{-3} lb/ton) for the hammers in the sweep section suggested that the restriction of the discharge was increasing residence time (and wear), as expected.

Probably a more significant indication of wear and a guide to hammer replacement requirements is the percentage of hammer wear. In this respect, the data in Table 2 indicate that station 7, at the top of the throat section, and stations 9, 10 and 11 in the grinding section, would have the shortest life. Hammer life may be represented in two ways: the maximum life - the end of which is marked by a hammer being thrown (breaking out of

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TABLE 2. HAMMER WEAR BY STATION

Evaluation Period: 11/4/77 - 5/4/78

Production Tonnage: 546 Mg (601 Tons)

		Hammer Description			Hammer Weight Loss	
Section	Station	No.	Type cm (in)	Weight kg (lb)	Individual Hammer kg/hammer/Mg x 10^{-3} (lb/hammer/ton x 10^{-3})	Percent Avg. wt. Loss ÷ Avg. hammer wt.
	1	-	-	-	-	-
	2	2	32 x 10 x 3.8 (12-1/4 x 4 x 1-1/2)	6.32 (13.93)	1.0 (2.0)	8.7
Prebreak	3	4	32 x 10 x 3.8 (12-1/4 x 4 x 1-1/2)	6.32 (13.93)	0.45 (0.90)	3.9
	4	2	32 x 10 x 3.8 (12-1/4 x 4 x 1-1/2)	6.32 (13.93)	0.55 (1.1)	4.8
	5	-				-
	6	-				-
Throat	7	8	8 Knife-H.F.	1.94 (4.27)	1.5 (3.0)	41.0
	8	12	12 6-Knife-H.F.	1.94 (4.27)	0.25 (0.5)	7.4
			6-Knife-N.H.F.	1.89 (4.17)	0.20 (0.4)	6.2
Grind	9	6	Axe-H.F.	2.90 (6.40)	1.0 (2.1)	20.1

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TABLE 2 (continued).

Section	Station	No.	Hammer Description Type cm (in)	Hammer Description Weight kg (lb)	Hammer Weight Loss Individual Hammer kg/hammer/Mg x 10^{-3}) (lb/hammer/ton x 10^{-3})	Hammer Weight Loss Percent Avg. wt. Loss ÷ Avg. hammer wt.
Grind	10	6	Axe-H.F.	2.90 (6.40)	1.8 (3.6)	32.5
	11	6	Axe-H.F.	2.90 (6.40)	1.3 (2.7)	25.6
Sweep	12	9	32 x 10 x 3.8 (12-1/4 x 4 x 1-1/2)	6.32 (13.92)	1.6 (3.3)	14.3

Total wt. loss = 32.34 kg = 71.23 lb = 0.1185#/ton

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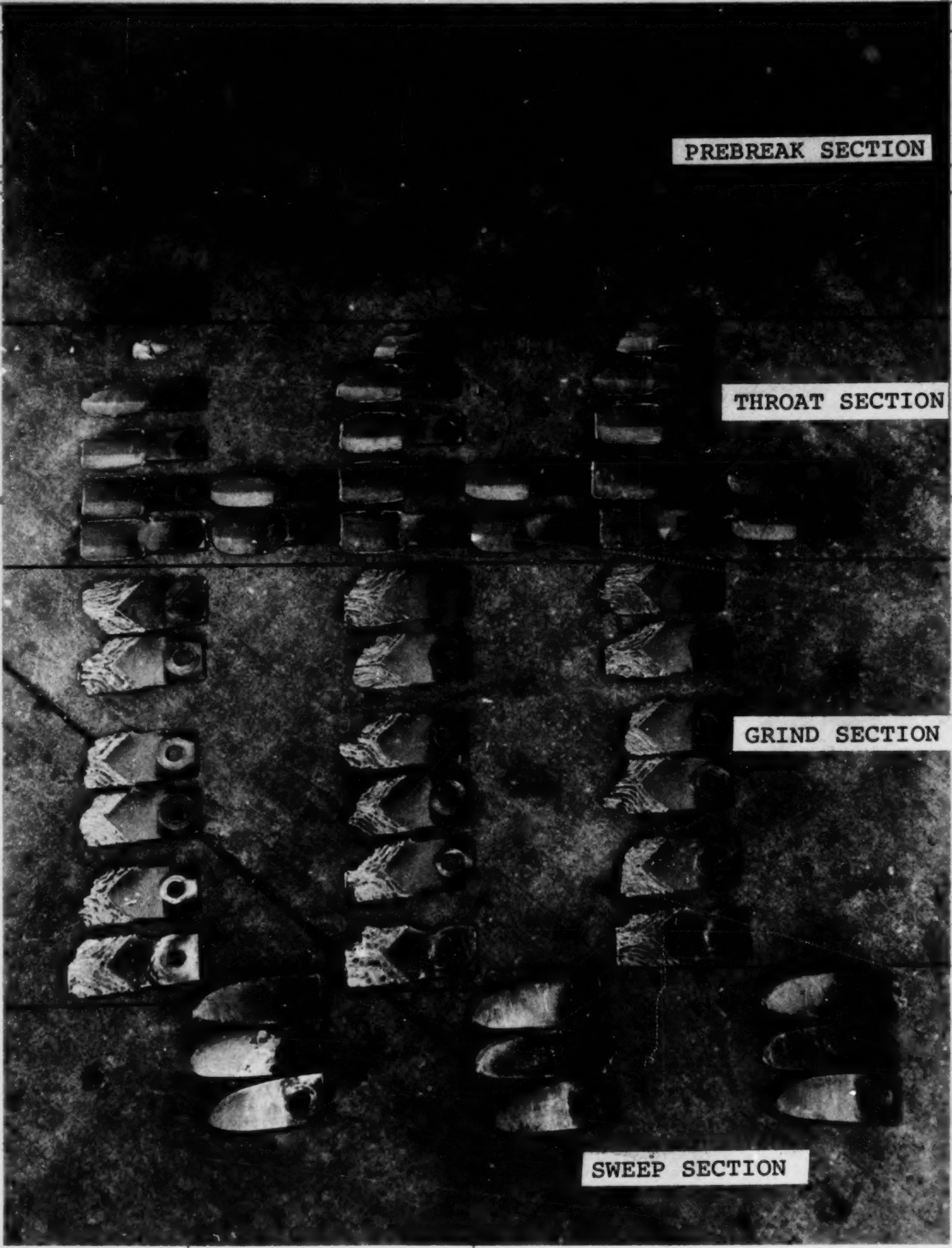
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THROAT SECTION
GRIND SECTION
SWEEP SECTION

Figure 8. Worn hammers after 546 Mg throughput.

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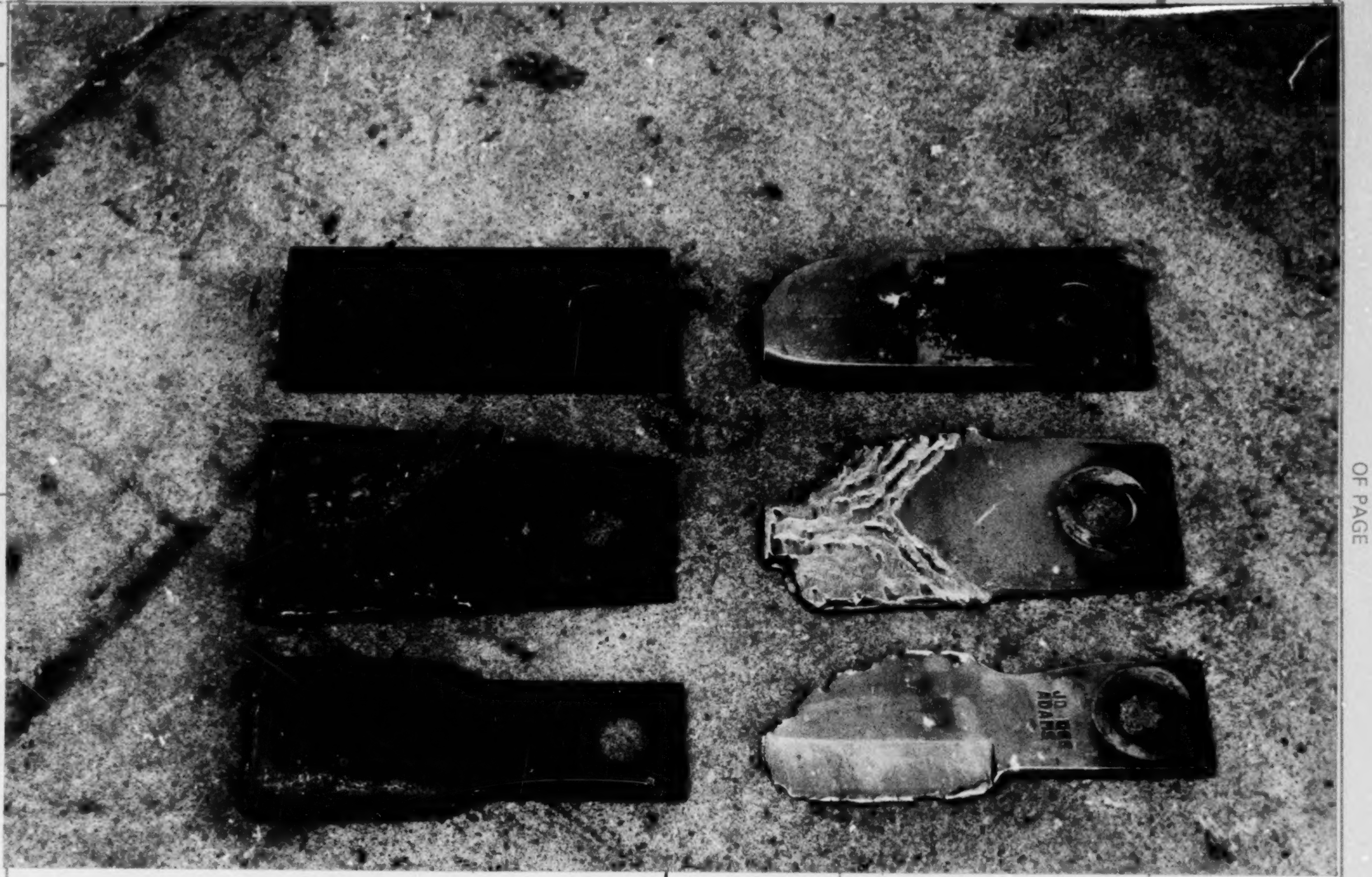

Figure 9. Typical new and worn sweep (top), axe (middle) and knife (bottom) hammers.

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the machine) - and the useful life - which is assessed by the ability of the set of hammers to produce the required product.

An indication of the maximum life of the knife-type hammers is available from the experience at station 7. One of the three hammers in the top row of station 7 was thrown after 546 Mg (601 tons) of throughput, thereby terminating the wear assessment period. Although the pieces of that hammer were not all recovered, the other two hammers at the same level showed weight losses of 50% and 62%. This would suggest that the maximum hammer life in this case is in the range of 50% to 60%.

To examine the useful hammer life, note the physical condition of the worn hammers at stations 7 and 10 (Figure 8). It is apparent that the wear has reduced their size and their usefulness significantly. The change in condition of the entire hammer set is apparent when one compares the product size distribution data. Figure 10 shows the mean size distribution from several samples early in the production cycle at 65 Mg (72 tons) and near the end at 520 Mg (572 tons). The minus 25 mm (minus 1 in.) fraction was reduced from 95% to less than 80%. While there is not a clear threshold size at which the secondary shred becomes unacceptable for densification, the worn hammer condition is indicated by the marked reduction in product size and an observed increase in frequency of pellet mill blockages. Assuming that the positions of the hammers would be periodically switched in the shredder to accommodate the varying weight losses, additional tonnage at acceptable product sizes could presumably be processed before hammer replacements were required. For example, if the hammers were interchanged in the throat and grind section until they were all uniformly worn down to 70% of their initial weight, an estimated 1,000 Mg (900 tons) could be processed before replacement was necessary.

From Table 2, the wear rate for the entire set of 55 hammers over the 546 Mg (601 tons) production is 0.06 kg/Mg (0.119 lb/ton). No comparable wear rates have been reported for secondary shredding of air-classified light fractions. However, for primary shredding of unseparated wastes, Vesilind has reported a wear rate of 0.041 kg/Mg (0.082 lb/ton) for a larger Heil-Tollemache Model 92B, and Diaz has reported wear rates of 0.013 to 0.106 kg/Mg (0.026 to 0.212 lb/ton) for eight different shredders tested [17,18].

Hammer wear in the grinding section (stations 9 to 11) was assessed for various hammer types and over the four production increments. The results expressed as the average specific hammer wear for the section and the average specific wear on individual hammers is presented in Table 3. The non-hardfaced knife hammers (period 1) and the non-hardfaced axe hammers of T-1 steel and A. R. (abrasion resistant) steel (periods 3 and 4) are

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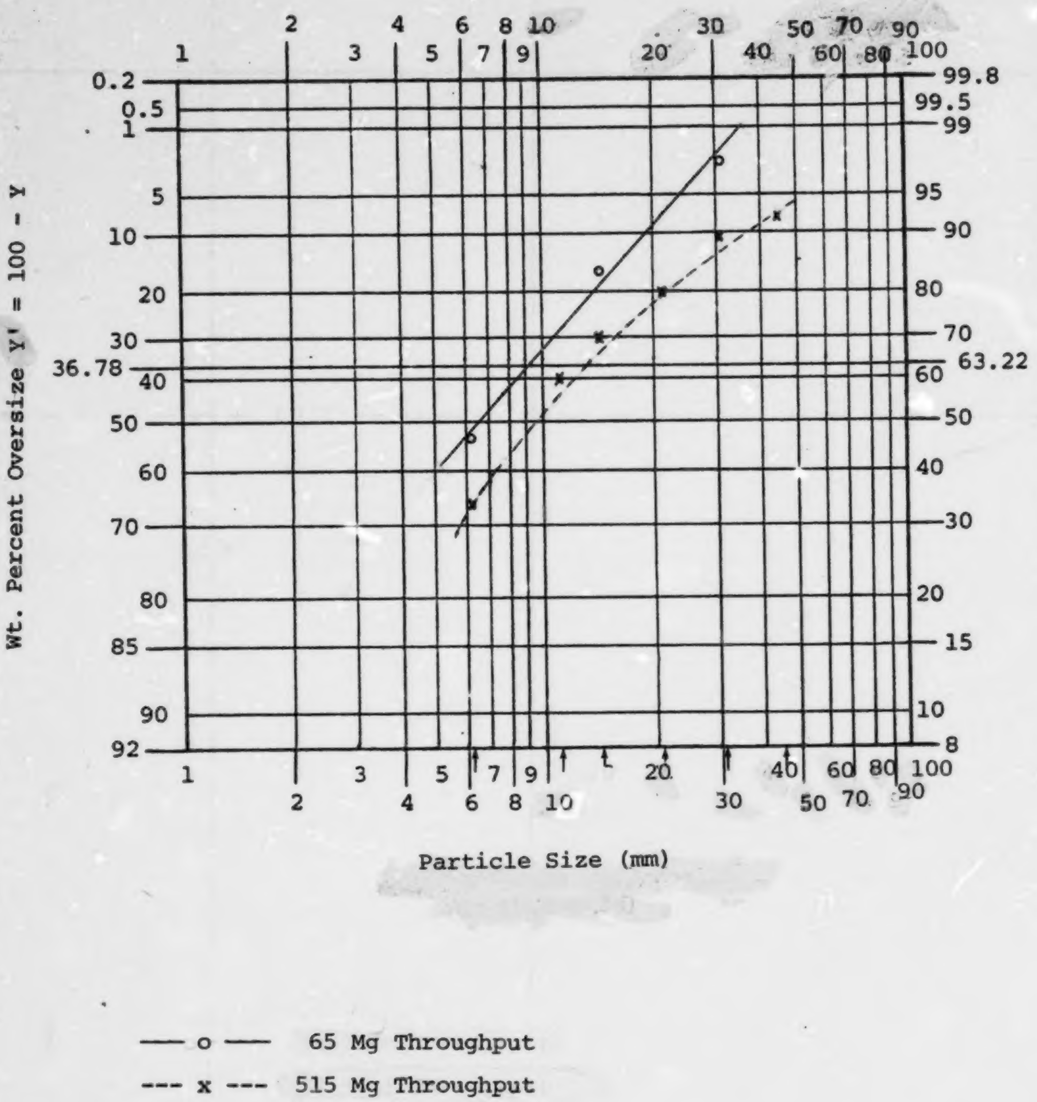

Figure 10. Effect of hammer wear on particle size distribution of secondary shredded light fraction.

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TABLE 3. GRINDING SECTION (STATIONS 9-11) HAMMER WEAR

Evaluation Period		Production Quantity	Hammer Description				Hammer Wear	
No.	Dates	Mg (tons)	Station	No.		Weight Avg. kg/hammer (lb/hammer)	Total Section kg/Mg x 10^{-2} (lb/ton x 10^{-2})	Individual Hammers (Avg.) kg/hammer/Mg x 10^{-3} (lb/hammer/ton x 10^{-3})
1	11/22/76-3/8/77	104 (115)	9-11	18	Knife-N.H.F.	1.89 (4.17)	7.0 (14.1)	3.9 (7.8)
2	11/4/77-5/4/78	546 (601)	9-11	18	Axe-H.F.	2.90 (6.40)	2.5 (5.0)	1.4 (2.8)
3	5/4/78-7/25/78	229 (252)	9-11	*6 6	Axe-H.F.	2.82 (6.23)		2.1 (4.3)
				6	Axe-T-1	2.40 (5.29)	4.8 (9.7)	2.9 (5.8)
				6	Axe-A.R. Stl	2.40 (5.29)		2.9 (5.9)
4	7/25/78-11/6/78	95 (104)	9-11	**15	Axe-T-1, A.R.	2.40 (5.29)	4.8 (9.7)	3.2 (6.4)

T-1 -- T-1 steel

A.R. Stl -- Abrasion resistant steel

H.F. -- Hardfaced - furnished by Mfg. - unknown base metal

N.H.F. - Non-hardfaced - furnished by mfg. - unknown base metal

*Hammer types distributed equally through each station

**Data on 3 hammers not available

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dimensionally the same as the hardfaced versions shown previously in Figure 9.

Not surprisingly, the greatest weight loss per unit weight processed was 3.9 x 10^{-3}/hammer/Mg (7.8 x 10^{-3} lb/hammer/ton) during the processing of the first 104 Mg (115 tons) of material. The hammer wear in this same section reduced to 1.4 kg x 10^{-3}/hammer/Mg (2.8 x 10^{-3} lb/hammer/ton) during the processing of the next 442 Mg (487 tons). This slower rate of wear is most likely due to the decreased hammer length and larger corner radius which resulted in a smaller contact area and angle of incidence between the hammer and feedstock.

KNIFE SHREDDER EVALUATION

An alternative to a hammermill for the secondary sizing is a rotary knife shredder. While it offers the benefits of pure shearing action, and grates to control product size, it is susceptible to damage from tramp metal and high wear from abrasive feedstocks. A brief evaluation of the operation and product from a rotary knife shredder manufactured by Triple/S Dynamics was undertaken during this program.

A sample of 240 kg (589 lb) of air-classified light fraction was collected and shipped to the Triple/S Dynamics' laboratory for testing. In view of the particular interest in the particle size distribution of the textiles stemming from their tendency to jam and stall the pellet mill, the test samples were seeded with 10% additional textiles.

A Model 24 Knife Granulator with a 75 kW (100 hp) motor was used for the test. Three interchangeable grates with circular openings of 13, 25 and 50 mm (1/2, 1 and 2 in.) were tested as well as operation with no grates at all. The particle size distributions of the air-classified, light fraction input for the 13 and 25 mm (1/2 and 1 in.) grates are shown in Figure 10.

The results from testing on the 13 mm (1/2 in.) grate are not reported. The product was extremely fine - all less than 6 mm (1/4 in.). It was observed to reside in the machine for long periods of time (presumably due to the restricted discharge area), limiting the machine capacity and resulting in the overgrinding.

The results from operations with no grates are not reported because there was no noticeable size reduction in the material as it passed through the machine.

The data in Figure 11 show the products from the knife shredder equipped with either the 25 or 50 mm (1 or 2 in.) grate would meet the presumed goal of 95% passing 25 mm (1 in.).

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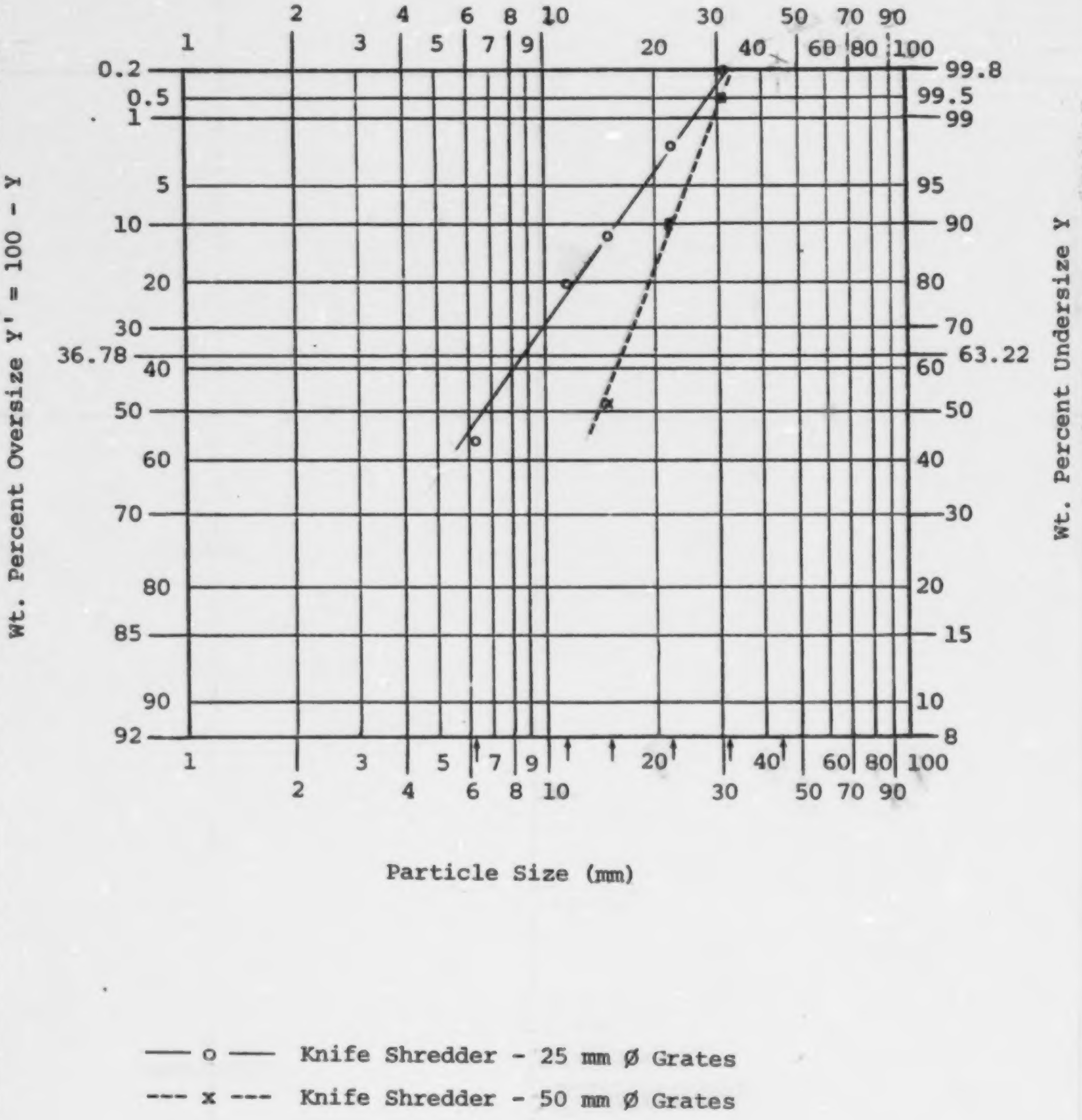

Figure 11. Knife shredder evaluation - particle size distribution of secondary shredded light fraction.

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However, the product from the 50 mm (2 in.) grate (about 45% under 13 mm (1/2 in.)) is significantly coarser than from the 25 mm (1 in.) grate (about 80% under 13 mm (1/2 in.)).

Comparison of the products from the knife shredder and hammermill is risky for a single test because of the effects of throughput, wear, and natural variability of such test results. However, the knife shredders, for either grate, clearly limit the topsize particles. The increased slopes as compared to plots for the Heil-Tollemache product in Figure 7 confirm this. The reason for the difference in the two slopes in Figure 11 is not known.

Because of small sample size and the handfeeding technique, meaningful throughput rate measurements could not be made. Dusting, or blow-back of material, was minor except in the 13 mm (1/2 in.) grate test where it was significant.

Knife granulators of this type have most applications in sizing scrap wire, electronic circuit boards, plastic and rubber at rates up to 1 Mg/h (1.1 ton/h). For air-classified light fraction, the volumetric capacity is expected to be the limiting factor rather than power requirements. Wire, lids, and other lighter gage ferrous and aluminum metal pose no problem to the shredder. However, heavier tramp metals, such as tools and hardware, can do serious damage if not removed by a magnet or other separation devices ahead of the shredder.

Although the rotary knives in most applications are adjusted within 0.11 mm (0.005 in.) of the fixed bed knives, it is not expected that such tolerances will be required for air-classified light fraction. The slight increase in power requirements and product size resulting from increased tolerances should not be significant. Nonetheless, the wear on the thinner knife edges will be more rapid than on the heavier, thicker grinder hammers. The actual wear rates and maintenance costs for the knife shredder could not be projected from the brief experience in this program.

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SECTION 3

DENSIFICATION

DENSIFIER DESCRIPTION

The generic types of densification equipment include pelleting, cubetting, briquetting and extrusion. This section provides a description of components and functions of the pellet mill and auxiliary equipment utilized in this program. The later discussions of the operation, maintenance and performance will utilize the nomenclature presented here.

A California Pellet Mill (CPM) Model B162 ring extrusion-type densifier (pellet mill) was used. Auxiliary equipment furnished with the pellet mill included a live-bottom feeder and mixer/conditioner. The majority of applications of the pellet mill are for pelletizing agricultural products. Some equipment modifications were required to facilitate the production of RDF. These are discussed below. Refer to Figures 12 and 13 in the following detailed component description.

Live-Bottom Feeder

Mounted above the pellet mill is the live-bottom feeder, which measures 2.4 m long x 1.4 m wide x 0.5 m deep (7 ft - 9 in. long x 4 ft - 6 in. wide x 1 ft - 6 in. deep). It contains four 58 cm diameter x 1.2 m long (23 in. diameter x 4 ft long) screws. Sheet metal side walls 90 cm (3 ft) high have been added to the sides to form a surge bin. The screws are driven by a 4.6 kW (7-1/2 hp) variable speed drive. The function of the live bottom is to provide a controlled, volumetric flow of material to the mixer/conditioner and pellet mill.

Mixer/Conditioner

This screw feeder is 56 cm diameter x 2.4 m long (22 in. diameter x 8 ft - 4 in. long) and is driven at 200 rpm by a 11.2 kW (15 hp) gear motor. The mixer/conditioner is so named because additives such as binders or lubricants (none used in this program) are blended into the feedstock at this point. In most pellet mill applications, rather than a screw conveyor, paddles are fitted on a center shaft to convey and facilitate agitation and mixing of the feed. Because of the tendency of

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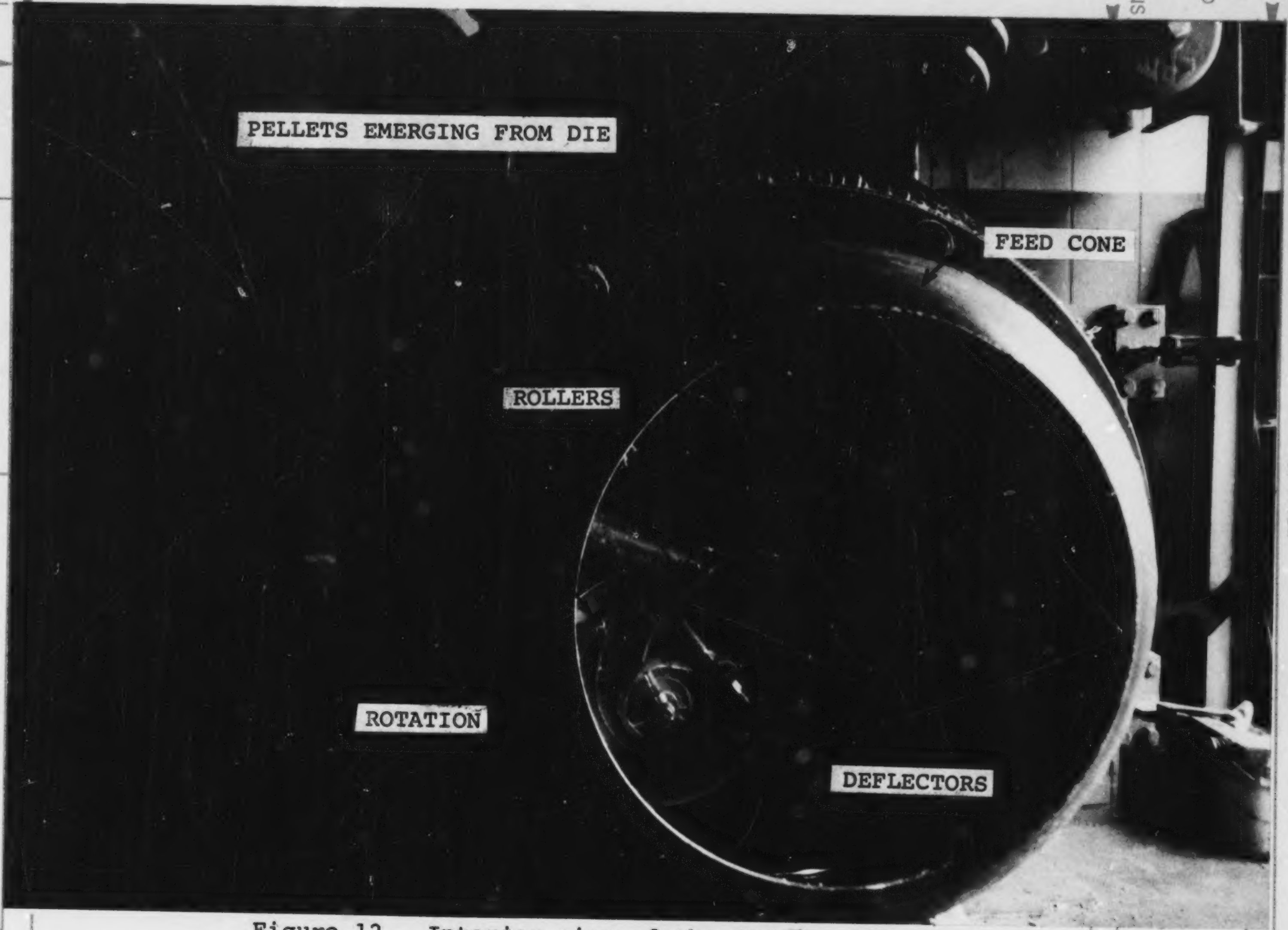
FEED CONE
PELLETS EMERGING FROM DIE
ROLLERS
ROTATION
DEFLECTORS

Figure 12. Interior view of the CPM densifier.

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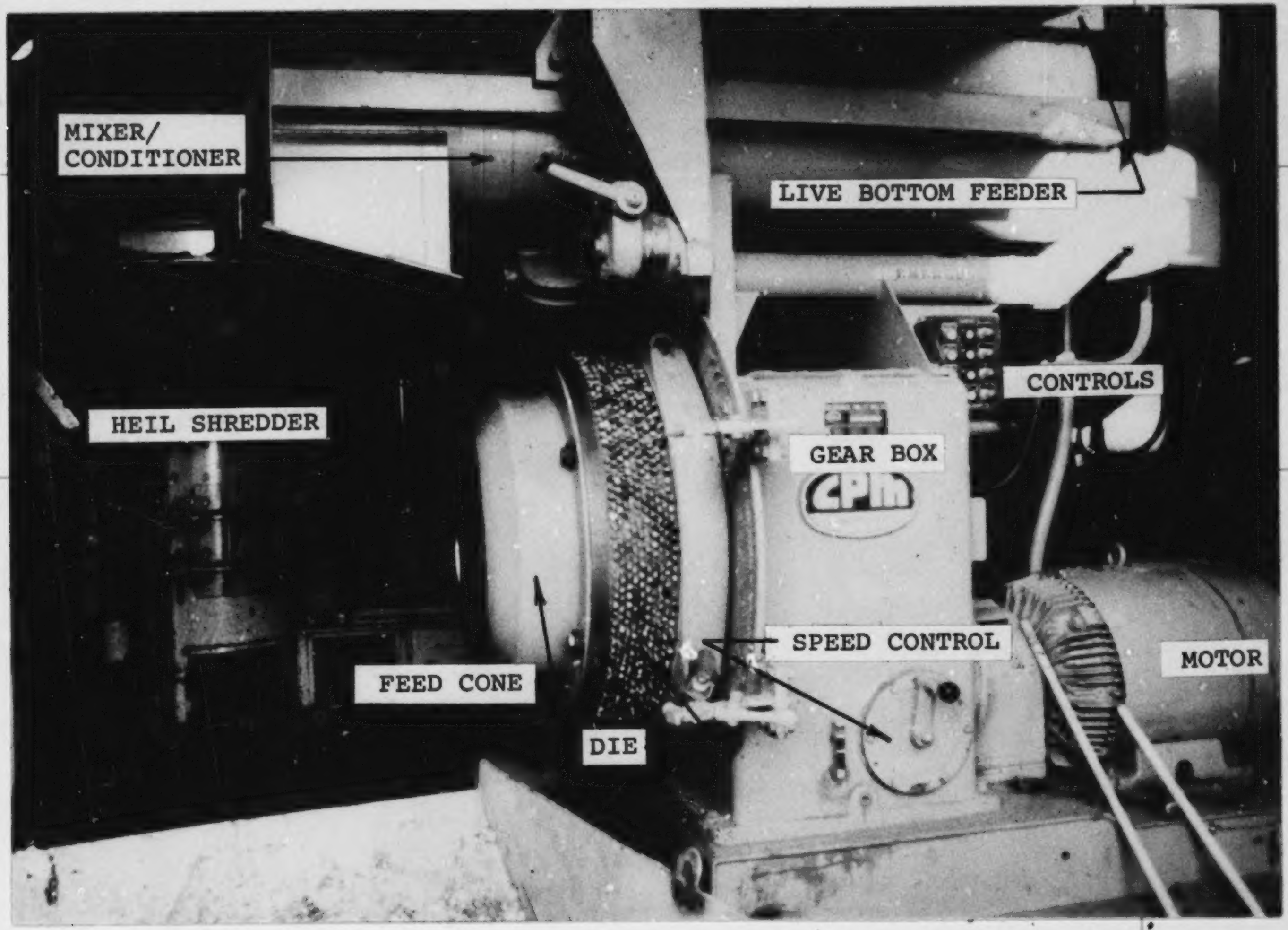
MIXER/
CONDITIONER
LIVE BOTTOM FEEDER
CONTROLS
HEIL SHREDDER
GEAR BOX
CPM
SPEED CONTROL
MOTOR
FEED CONE
DIE

Figure 13. Exterior view of CPM densifier (door and Even-Flow not shown).

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the paddles to snag and clog with string and textiles, a continuous screw was furnished for this application.

Even-Flow Feeder

This screw feeder receives the material from the mixer/conditioner screw and accelerates and distributes feed into the mill feed capacity. The screw is 50 cm diameter x 75 cm long (20 in. diameter x 30 in. long) and is powered by a 5.6 kW (7-1/2 hp) motor turning at 300 rpm.

Feed Cone, Deflector and Wipers

Distribution of the feed from the Even-Flow feeder to the wedge formed by face of the roller shells and face of the die is accomplished by three components: the feed cone, the deflectors and the wipers. The feed slides down into the feed cone and is carried by raised edges on the cone into two stationary deflectors. These deflectors, supported by the fixed outer roller supports, then move the material out of the cone and into the roller/die wedge. On the other side of the die are two wipers supported on the rotating mainshaft disc that collect the material that has carried past the die and direct it back from the rear into the roller/die wedge.

Rollers

Two idling rollers are mounted inside the die cavity on eccentric shafts so the position of the rolls can be adjusted to a selected clearance between the roller face and die surface. Rotation of the die in contact with the rollers causes the rollers to turn.

The rollers for this model machine are available in 25 cm (10 in.) and 33 cm (13 in.) diameters and with several types of surfaces. In this program, corrugated and textured (hard coat) surfaces were investigated.

Die

The die is a steel alloy, perforated cylinder, through which the feedstock is forced in forming pellets. The inside diameter of 75 cm (30 in.) and width of 16 cm (6-3/8 in.) give a working surface of 3,075 cm^2 (476 $in.^2$). The hole diameter, inlet taper angle and taper depth of the die are all variable and selected for the material and application. Die selection for this program will be discussed later.

A two-speed gear assembly rotates at 98 rpm or at the nominal 170 rpm. A shear pin assembly acts to protect the densifier from shock loads induced by rapid stoppages of the die. There

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are two shear pins of selected strength that will break to free the mainshaft so the rollers and die can rotate together.

Motor

The drive train and frame is designed for a 112 to 150 kW motor. A 112 kW (150 hp) motor was used during this program.

Breaker Bar

A fixed metal plate was added to the top of the shell door enclosing the die. The plate acts to break off the pellets at a pre-determined length of nominally 30 mm (1-1/4 in.) as they are extruded.

Control

Local stop/start push buttons and indicator lights were located on the pellet mill, to allow for quick stops or to jog the mill to clear jams.

DIE SELECTION

The densifier capacity and product quality are greatly influenced by the die configuration. Dies were available with hole openings of 2 to 32 mm (1/16 to 1-1/4 in.) and with a range of hole dimensions. These parameters include entry taper, depth of taper, angle of taper, length of pelleting hole and depth of relief taper.

The selection of pellet size was governed by the need to match the handling, feeding and combustion characteristics of stoker or particle coal having a nominal 13 to 38 mm (1/2 to 1-1/2 in.) particle size. The pellet length could not be narrowly controlled, but it was estimated it would fall in random lengths up to 32 mm (1-1/4 in.) controlled by the breaker bar. Smaller diameter pellets would require greater, more costly feedstock size reduction. With larger diameter pellets, there were concerns of poor flowability and a lower bulk density which would limit the boiler feed capacity.

In selecting the die hole configuration, the manufacturer contended with additional considerations of capacity, feedstock properties, power consumption and wear. At the time of equipment specification for this program, there had been no significant operations on solid waste feedstocks; consequently, the selection was based on engineering judgment rather than experience.

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The results of these numerous and diverse parameters were the selection of two dies, one with 13 mm (1/2 in.) and one with 25 mm (1 in.) diameter holes. Both had a moderate or mid-range taper configuration (manufacturer's details proprietary). Both dies were utilized, although 13 mm (1/2 in.) pellets accounted for more than 90% of the production. A second 13 mm (1/2 in.) die was procured and used during the late stages of the program.

ROLLER SELECTION

Initially, the manufacturer supplied the standard 25 cm (10 in.) diameter rolls with a corrugated surface. Early problems with blockages led to a change to the larger 33 cm (13 in.) diameter corrugated rolls. The larger rolls provide a lower angle of incidence with the die and thus insure a more positive nip of the feedstock. Later, 33 cm (13 in.) rolls with a textured, hard coat surface were tried. The objective was to reduce the wear rate on the rolls by use of a hardfaced surface covering. The experiences in using these different types of rolls will be discussed.

DENSIFICATION PROCESS

A description of the densification process is relevant to later observations and data on equipment operation and pellet properties.

As material is fed to the die cavity, it is flattened against the die by successive passes of the rollers. Layer after layer builds up forming a pad until the material is punched radially outward through the die holes. A tapered hole inlet provides some lateral compaction, while the resistance from the taper and from the movement through die holes compacts the pellet along their axis.

The layers of material can be seen as lateral planes running across the pellet diameter. Rather than straight, they tend to be convex in the direction of extrusion due to the resistance of the hole sides. This can be seen in a picture of typical pellets in Figure 14.

Often these layers will consist of a piece of plastic or textile. These materials often bind poorly with the adjacent layer of paper and form a weak shear plane where the pellets are more susceptible to breakage.

The layering is particularly evident when the pellet becomes wet. The moisture penetrates the sides and causes the layers to delaminate and form a ragged scaly, surface. Such pellets are then more easily broken into smaller pellets or flaky fines.

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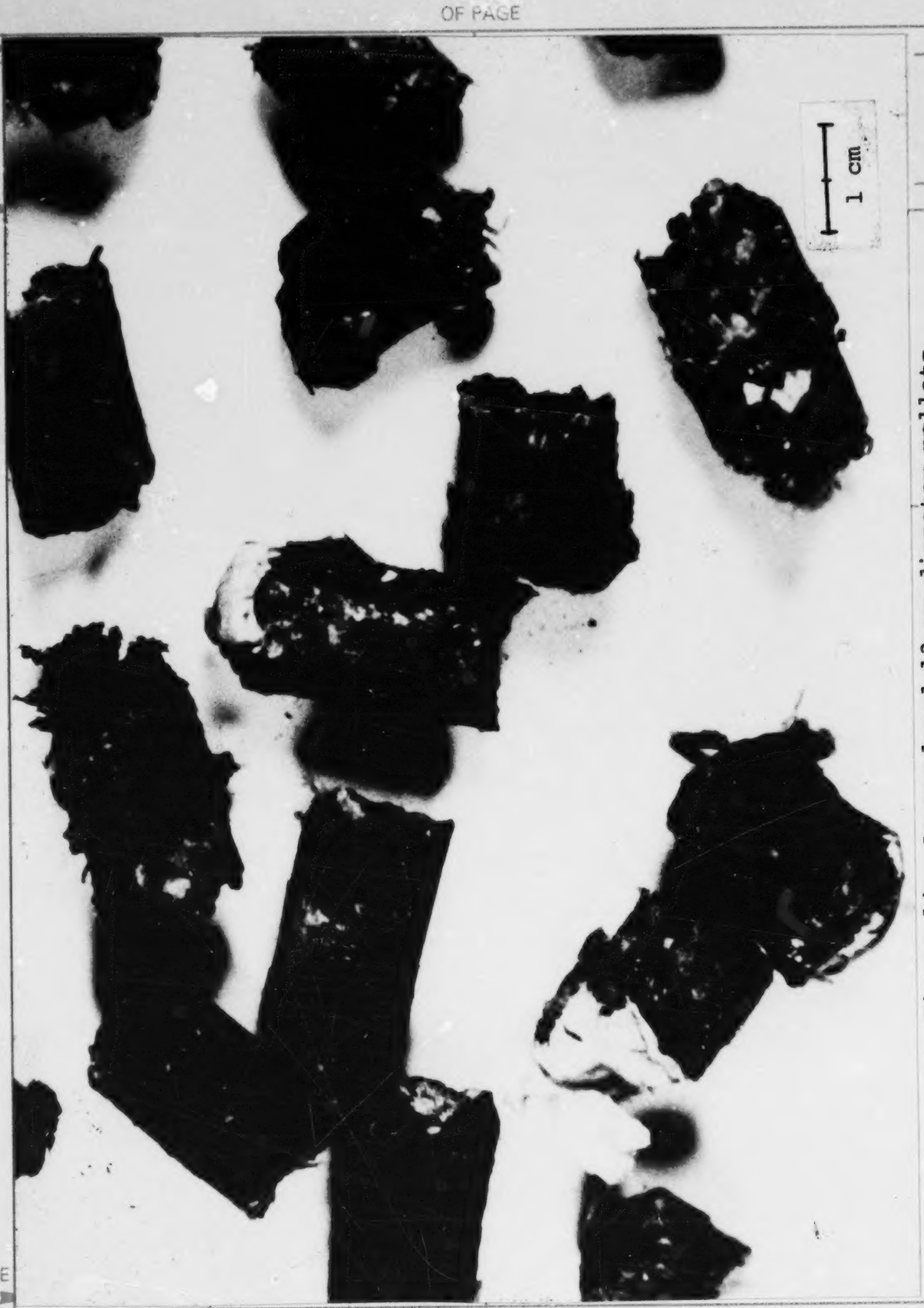

Figure 14. As-produced 13 mm diameter pellets.

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The mechanism that bonds refuse-derived fuel pellets is not fully understood. With wood and agricultural feedstock, natural binders in the form of lignin are present. Often steam is used to condition and soften the material. For some applications, binders such as paraffin, lignin or bettonite (clay) are added. For residential waste feedstock, it seems the available moisture (ranging from 15% to 30%), and presence of some lignin, waxes and greases all play a part in binding the material.

The pellets are extruded from the outside of the die and are broken off in random lengths, either from the centrifugal force of the whirling die, by contact with other pellets in the discharge enclosure, or by striking the pellet breaker bar.

DENSIFIER OPERATIONS AND THROUGHPUT

The experience of processing 1,300 Mg (1,400 tons) of RDF into d-RDF provided significant insights on the selection, installation, shakedown operation and performance of the pellet mill and auxiliary equipment. The following discussion will highlight the measurements and observations on the densifier that may be instructive in design, implementation or evaluation of densification technology.

The early expectations of production rates of 7 to 9 Mg/h (8-10 ton/h) through the pellet mill were never realized in this program. There appears no single or simple explanation for this, or even a clear answer as to actual capacity. A number of interrelated factors influence the performance and capacity of the pellet mill.

(1) Equipment configuration

(2) Die and roller condition

(3) Stability of feedrate

(4) General feedstock properties including moisture, density and particle size

(5) Presence of oversized textiles

Because of the interrelation of these factors, they will not be discussed individually but in the context of a discussion of efforts to maximize throughput and observations on equipment operations.

Shakedown Operations

Efforts in the first few months to achieve significant throughput rates were unsuccessful, due to frequent system

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blockages and downtime. About one-half of the interruptions were attributable to problems in the feed preparation equipment and one-half to jamming in the densifier. Many minor problems were resolved by working with the manufacturers and equipment. The investigations and changes to the secondary shredder in attempts to control oversize textiles were made and completed during this period (see Section 2). Startup and operating routines were refined as the operators gained experience. System availability and throughput rates increased to the point that meaningful measurements could be made so data collection was initiated.

Feedrate Control

The feedrate to the pellet mill was controlled by setting the speed control on the live-bottom feeder. The pellet mill operator set the speed control according to the stage of operation (to establish pad, warmup transient, etc.). The manufacturer's instructions suggested increasing the feedrate until reaching the normal motor load (current). In this program, the motor current routinely fluctuated for periods of several seconds to one-half minute in magnitudes of 20% to 50% of full load. Adjusting flow to such a varying load proved frustrating. More typically, the feedrate was increased in small increments until the frequency of blockages increased notably or until, by virtue of sounds or the current indicator, the operator knew the motor was fully loaded or near stalling.

The feedrate of secondary shredded light fraction to the live-bottom feeder was adjusted by controlling the input rate to the primary shredder by the shredder operator. This arrangement required significant operator skill and attention to maintain a uniform rate of feed to the live-bottom feeder. Even then, fluctuations in flow resulted from buildups and surges in the air classifier and in the mechanical and pneumatic conveyors. Undoubtedly, an improved flow control system, different than that used at ETEF, is required to maintain a steady, controllable feedrate to the densifier system. Such a system would include added surge capacity to absorb flow fluctuations from the shredder and air classifier and a sensing system to measure and adjust volumetric feedrate.

Throughput Rate Measurements

The throughput at the densifier was measured on 500 or more occasions over 15 months of operation. The d-RDF product was collected in a scale-mounted hopper and the fill time and hopper weights recorded. The time increments varied from 2 to 20 minutes depending on the rate of production and blockages or other interruptions in the production. Unless noted, all rates reported are for the actual production periods, that is, for the period which waste was being fed to the densifier. Downtime is not included in computation of the production rate. Many of these measurements were made in nominal operating conditions, where a balance was sought between maximum rates and minimized downtime due to blockages; however, numerous other runs were made in an attempt to maximize throughput disregarding consequences. Typically, however, these high throughput operations >4.5 Mg/h (5 ton/h) were not sustained for more than several minutes before a jam occurred in the pellet mill. During the first 45 Mg (50 tons) of production, the average production rate was 2.0 Mg/h (2.2 ton/h) with a peak rate of 5.5 Mg/h (6 ton/h) for periods of up to 30 minutes.

After 182 Mg (200 tons) of production, the nominal throughput had increased to 2.2 Mg/h (2.4 ton/h) with several test peaks of 6.8 Mg/h (7.5 ton/h). This additional throughput, although slight, was probably attributable to operational experience and to mechanical changes to the plows and shear pins. Unfortunately, frequent equipment modifications, both in the densifier and feed preparation equipment (air classifier and shredder), and the difficulties in maintaining a constant feedrate over a long period prevented any correlation of throughput with moisture, grind, air classifier recovery, etc.

Equipment Condition

The impact of the condition of the die and rolls on throughput is demonstrated in comparing two later rate measurements. After some 635 Mg (700 tons) on the 13 mm (1/2 in.) die, throughput rate measurements indicated an average throughput at 2.2 Mg/h (2.4 ton/h), which was very close to the earlier results. However, the frequency of jamming was increasing and so the old worn rolls were replaced with new rolls. The first measurement of throughput rate made during the first several hours showed average production rates increased to 3.2 Mg/h (3.5 ton/h). The new rolls, with sharp corrugations, more positively nipped and pressed the material and were thus less susceptible to jamming. This allows the operator to increase the feedrate without experiencing a related increase in jams.

When a die that had been reground flat, or a new die was installed, a similar reduction in jamming was apparent, and the feedrate was increased accordingly. The sharper corners at the die holes apparently shear the waste more easily and thus are less susceptible to problems with textiles.

For neither case with the new dies nor rolls was the improvement long lived. After less than 45 Mg (49.6 tons), this very abrasive feedrate had blunted the sharp edges and the nominal densifier capacity was reduced accordingly.

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Surging

The fluctuations in motor current mentioned earlier were noticeable even when the flow from the live bottom was observed to be quite consistent. This suggests that flow interruptions and surges may have also been developing within the densifier. This view was enforced by the noted sensitivity of the densifier performance to changes in the size and orientation at the deflectors and wipers used to keep material moving through the die cavity.

It is postulated that the feedstock, particularly lower density feedstock, may have temporarily bridged in the feed cavity between the roller support assembly and cone. As more feedstock continued to enter, it would suddenly push these clumps into the nip of the roller and die, momentarily exceeding the capacity of the machine to compress it; current surges and blockages resulted.

The low and varying feedstock density is felt to be a primary contributor to this surging. Measurements of the secondary shredded waste showed a range of 25 to 64 kg/m^3 (1.5 to 4 lb/ft^3) with a mean of 40 kg/m^3 (2.5 lb/ft^3). The variability was due to differences in composition, moisture and particle size of the waste. For comparison, the typical feedstock densities for feed and wood waste applications of the densifier were 112 to 160 kg/m^3 (7 to 10 lb/ft^3); also, significantly less variation is experienced than with processed wastes. These more consistent higher density feedstocks did not exhibit the surge and jam characteristics observed with residential wastes, a fact which supports the hypothesis.

Blockages

Plugging in the pellet mill, which occurred in a random pattern, resulted when material jammed in the wedge formed between the face of the die and the face of the rollers and was not extruded. The rolls would then stop and would increase friction and resistance to the rotating die. Sometimes this occurred slowly over several seconds - where the motor load increased until it stalled or was shut down by the operator or high current protective circuits. Oftentimes the jam resulted in a rapid, or shock, loading on the rotating die which broke the shear pins.

The circumstances that triggered a blockage are generally known but not always identifiable for each occurrence. The wedge of material jammed between the die and the rolls had frequently been observed to include an oversized 8 to 20 cm (3 to 8 in.) piece of textile. Other times, it was apparent that the pad normally covering the surface of the die had broken loose from the die face and slugs of this dense material wedged hard

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in the die/roller interface causing the rollers to skid and stall the die. While it is possible that textiles may have been responsible for dislodging the pad, such occurrences could also have been triggered by moisture or other feedstock properties or components. Occasionally, the pad was observed to transfer from the surface of the die and wrap around the surface of the rolls with a blockage resulting.

Shear pin failures characterized all of the earlier plug-ups. Under the direction of the manufacturer, the strength of the shear pins was successively increased up to a limit necessary to protect the machine. While the incidence of shear pin failures declined markedly, blockages persisted. However, rather than breaking shear pins, the blockages stalled the die and then the motor.

Motor Size

Consideration was given to increasing the size of the pellet mill motor from 112 kW (150 hp) to 150 kW (200 hp) in an attempt to override the tendency to jam. Unfortunately, this was not accomplished in the course of the project. It is, however, instructive to note the experiences with pellet mill blockages related by operators at the Maryland Environmental Services Resource Recovery Facility in Cockeysville, Md. [19]. An identical densifier and 13 mm (1/2 in.) die are used on a lower ash, residential waste feedstock. Except for a larger 150 kW (200 hp) motor, their experiences and achievements in throughput rates and problems with textiles had also been similar to those at ETEF. However, the mode of failure resulting from a blockage was not with a stalled motor, but with shear pin failures, or with jamming and stalling in the Even-Flow feeder. Apparently, as a wedge of material jammed and stopped the rolls, the die may have continued to turn and slip past the stalled rolls. The feedstock filled the die cavity, then backed up into the force feeder and stalled its drive. In view of this alternate failure mechanism, increasing the size of the densifier motor to override a potential jam may not be as simple a solution as it first appears.

Equipment Adjustments

During densifier operations, adjustment of the roll positioning to fit equipment and material condition is necessary. A cool die will have material left in the holes that has hardened and dried. To break loose these pellets, the rolls are brought down tight against the die and material slowly fed. As the holes are cleared and the die heats up, the rolls are repositioned outward. Optimum production for the residential waste feedstock appeared to be at a pad depth 3.2 mm (1/8 in.) and slightly less with wet material or with more worn dies or rolls.

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Pellet Cooling and Screening

Although not applied in the system at ETEF, in most densifier applications, the pellets are cooled in a pellet cooler following the densifier. A pellet cooler is simply a mesh conveyor for transporting a thin layer of pellets through a fan-induced air stream. The objective is to reduce the pellet temperature from 80° to 90°C (180° to 190°F) at which they are produced to near ambient temperatures. The advantage of cooling immediately after production is to harden the pellets through the evaporation of surface moisture and solidifying some of the binding waxes, lignin, etc. The cooler, firmer pellets are less susceptible to breakage and, presumably, to onset of biological activity. During the production program, it was noted that the warm, steaming pellets would maintain their temperatures during transport and handling. While not necessarily the only factor influencing the biological reactions later observed in storage (Section 5), the elevated temperature could accelerate the onset of such conditions.

Pellet coolers are often accompanied by a screen to sieve unpelletized fine material. The screen opening is generally slightly smaller than the pellet diameter. The purpose is to remove and recirculate fines to the densifier inlet, thereby increasing the final product density and yield and reducing dusting.

POWER CONSUMPTION

The power consumption of the pellet mill is a function of densifier configuration (die and roller size and condition), the feedstock properties (particle size, composition and moisture), and the throughput rate (average and surges).

More than 500 measurements of power consumption and throughput were taken during the production period. The results have been reported previously [20,21]. However, discovery of errors in connections of the recording wattmeter were made after conclusion of the project, and all of the measurements were found to be incorrect and unrecoverable. These previously reported results are hereby withdrawn [20,21].

From observations of the motor current during production, a gross indication of power consumption is available. Although the motor currents at particular throughput rates were not recorded, the current readings were frequently observed as a guide to feedrate control. For the nominal throughput rates of 1.8 to 2.7 Mg/h (2 to 3 ton/h) with moderate worn dies and rolls, the motor current fluctuated between 105 to 125 amperes. Taking means of these observed ranges, at 2.3 Mg/h (2.5 ton/h), the motor current would be 115 amperes.

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The motor current for the 112 kW (150 hp) wound rotor motor operating at full load and with a power factor of 0.9 would be 157 amperes. Thus, at the 2.3 Mg/h (2.5 ton/h) and 115 amperes, the motor is operating at 73% of full load. Expressed in kilowatts, the power requirement at 2.3 Mg/h (2.5 ton/h) would be 82 kW or 36 kW/Mg/h.

Considering the fluctuations in load from surging, this calculation suggests that there was limited margin available above 2.7 Mg/h (3 ton/h) feedrate with the 112 kW (150 hp) motor. The substantially higher measured throughput (up to 7 Mg/h or 7.7 ton/h) may be explained by its occurrence primarily at early stages of production when the die and rollers were less worn. The power consumption would be expected to be less as the material was more positively gripped and sheared through the holes.

A subsequent research project for the Urban Waste Technology Branch, Department of Energy, investigated the effect of addition of waste oil to the densifier feed product on, among other things, the power consumption and throughput [22,23]. An office waste feedstock (mainly paper, rather than mixed municipal waste) was used for the testing. Power consumption is reported for various throughputs (0 to 2 Mg/h or 0 to 2.2 ton/h dry) and oil and moisture levels. For a comparable mean throughput of 2.3 Mg/h (2.5 ton/h) at a 20% moisture content (no oil), these data showed a power requirement of 125 kW, or 55 kW/mg/h (50 kW/ton/h). The explanation for the higher than predicted power consumption for the high paper content waste is not known, although it could be related to the difference in composition of the two waste feedstocks.

ONE-INCH PELLET PRODUCTION

The 25 mm (1 in.) die was used for a short period during shakedown operations and reinstalled later in the project for production of some 90 Mg (100 tons) of pellets. Because of the intermittent operations and low throughput rate, the earlier experience was not representative of later sustained operations. The waste was drier and combined with the low throughput (less than 0.9 Mg/h or 1 ton/h) produced an uncharacteristically hard, dense pellet. More typical moisture and production rates of 3.2 Mg/h (3.5 ton/h) were achieved in the second period. However, pellet and bulk densities of the 25 mm (1 in.) product were more than 30% lower than the 13 mm (1/2 in.) pellets (Section 4). Due to concern of introducing handling and feeding problems at the boiler related to these lower densities, production of the larger pellets was terminated and production of 13 mm (1/2 in.) pellets was resumed.

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The difficulties in achieving densities in the 25 mm (1 in.) pellets comparable to densities with the 13 mm (1/2 in.) pellets were unexpected, since experiences by the manufacturer with other feedstocks were to the contrary. The problem was attributed to insufficient hole taper in the larger die. The selection of the taper was based on a series of compromises and assumptions. Unfortunately, project schedules and resources did not permit evaluation of more severely tapered dies thought likely to produce the increased densities.

The 25 mm (1 in.) die was tried in hopes of reducing the frequency of jams and thereby increasing the reliability and availability of equipment. Based on the manufacturer's experience, and since the open area of the two dies is essentially the same, an increase in actual capacity was not expected.

Observations and rate measurements of the 25 mm (1 in.) die indicated an initial reduction in blockages and a throughput rate equal to the previous high levels of 3.2 Mg/h (3.5 ton/h). But after the first 45 Mg (50 tons) processed, blockages characteristic of the earlier ones began to reappear. It is felt that as the edges of the new die and corrugations of the new rollers were worn down, the ability to grip and shear the material was reduced and the jams reoccurred.

The production period with the 25 mm (1 in.) die was too short to obtain data on wear or power consumption.

Future work on 25 mm (1 in.) pellets with dies of more severe tapers is warranted. If pellet and bulk densities comparable to the 13 mm (1/2 in.) pellets can be attained, and the maximum pellet length is controlled to 25 mm (1 in.) by the breaker bar, handling and firing properties of the 25 mm (1 in.) pellets should match those of the 13 mm (1/2 in.) pellet. Also, the benefits in production of increased reliability and reduction in feedstock sizing requirements would be gained.

DENSIFIER MAINTENANCE

The wear on the die and roller shells is the most significant component of the maintenance requirements and expenses. Replacement costs of the die and rollers may run to more than $8,000 (1979 cost). The wear patterns are similar to those observed by the manufacturer for other feedstocks, but occurred at a faster rate due to the higher levels of inorganic fines and other abrasive materials in the waste. (Even cellulose is abrasive.)

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Roller Wear

The 33 cm (13 in.) corrugated and textured-type roller shells utilized in this program are pictured in Figure 15. Although 25 cm (10 in.) diameter rolls were utilized during short segments of production, wear for these smaller rolls was not measured. The textured-type rolls had a rough, hard-coat surface, but tended to smooth and polish rapidly and lose their ability to grip the material. As the corrugated rollers wore, the corrugations were flattened and smoothed. Figure 16 shows a 33 cm (13 in.) corrugated roll after some 550 Mg (606 tons) throughput. This is the upper roll (right-hand) and the less worn of the two rolls in the pelletizer. The left-hand lower roll was observed to wear slightly faster due to the effects of gravity on the distribution of the material. Note the nine valleys across the face of the rolls. They correspond to the location of rows of die holes. The greater wear at the hole inlets could be expected from the movement of feedstock, toward and into the holes.

6-1/2"

Not so apparent in the photograph is the concave surface developed across the face of the rolls. This is presumed to have resulted from the increased throughput (and thus abrasion) occurring at the center of the die and roller.

9-1/8"

Measurement of a set of new 33 cm (13 in.) diameter rolls showed a slot depth of 0.35 cm (0.135 in.). After 550 Mg (606 tons), the lower and upper rolls had worn to outer edge diameter of 32.0 and 32.3 cm (12.6 and 12.7 in.) and center diameters of 31.6 and 31.9 cm (12.5 and 12.5 in.) respectively. The 0.4 cm (0.16 in.) difference between outer and center diameter in both cases represents the concave face profile. The procedure used for these measurements is included in Appendix C.

The pellet mill performance at the late stages of use of these worn rollers was characterized by increased frequency of jamming and blockages. Noting the near absence of corrugations on the roller, the roll condition was assumed to be the cause and the rolls were replaced. Unfortunately, aforementioned difficulties with the textured surface rolls and metallurgical failure of two additional sets of corrugated rolls did not permit sufficiently long operation to obtain comparative wear data on any other rolls.

The 550 Mg (606 tons) roller life is shorter than experienced in any other densifier application, and is indicative of the abrasive characteristics of a feedstock with the higher levels of inorganic fines. Use or extrapolation of these results should recognize these specific conditions. Separation techniques to reduce these abrasive fines are available and hold promise of extending the roll (and die) life significantly.

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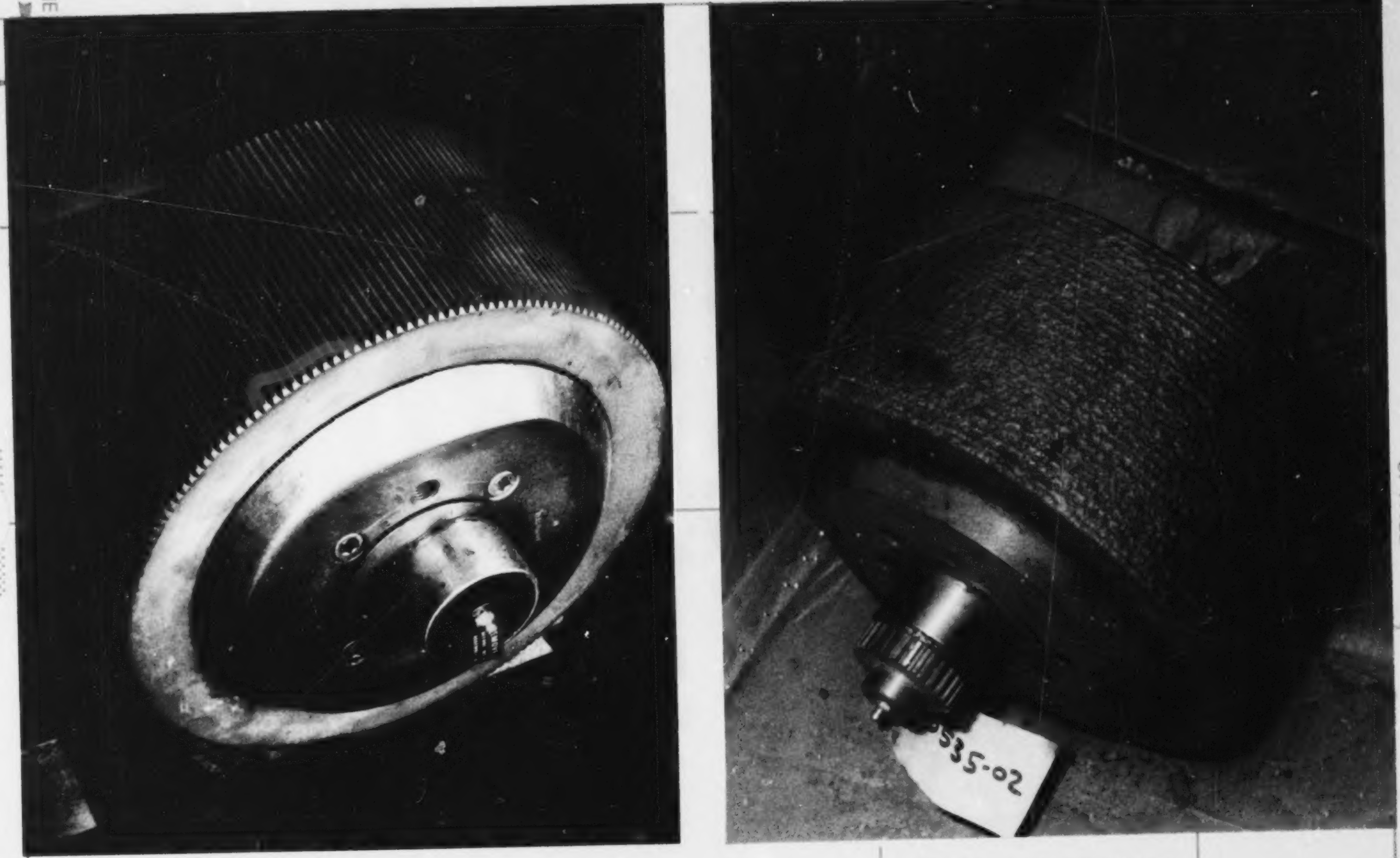

Corrugated Surface

Textured Surface

Figure 15. New 33 cm diameter corrugated and textured surface rolls.

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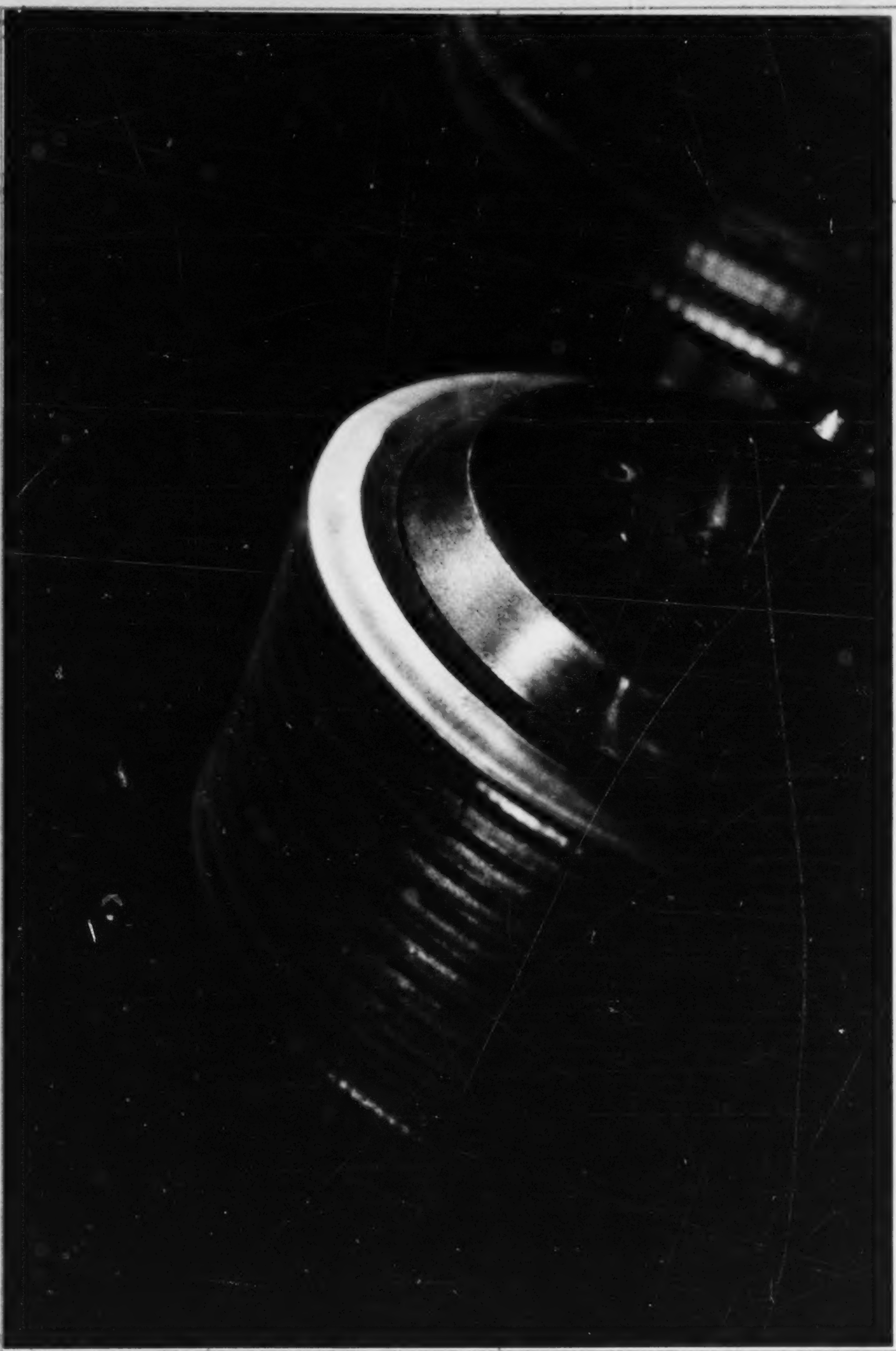

Figure 16. Worn 33 cm diameter corrugated roll after 576 Mg throughput.

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Die Wear

Dies with 13 mm (1/2 in.) and 25 mm (1 in.) holes were used during the course of the test program. The larger die was used only briefly and, consequently, observation and measurements of wear were made only on the 13 mm (1/2 in.) die.

As the die wears, the sharp edge at the hole inlet is blunted; over a longer period, the inlet diameter widens and the land area between the holes is reduced. The worn die, like the rollers, develops a slightly concave surface as a result of the increased material movement at the center of the die face.

A procedure to measure die wear rate had to be developed in the absence of any previous techniques for obtaining such data. It involved measurements of the change in depth of the active die face which were taken from a fixed plane not part of the wear surface. Measurements were made along four columns of holes parallel to the axis of rotation and 90° apart around the periphery of the die. A control, or baseline, series of measurements were taken for statistical comparison to later measurements to determine the change in depth (and wear) as a function of throughput. A copy of the procedures is provided for reference in Appendix C.

The technique itself proved difficult to perfect. Two jibs were tried before confidence in measurements was developed. Still, the non-uniform surface, with occasional pits, burrs and changing hole tapers, caused radical and unrepresentative changes in readings from one period to the next. Locating the depth gage at an identical location was also difficult. As a result, changes in the die surface, over a relatively short production of up to 200 Mg (220 tons), were not shown to be statistically significant.

Measurement between longer periods of production were thwarted by unprogrammed equipment changes. Whenever rolls are changed (as necessary because of wear or because of metallurgical problems which was the case on two occasions), wear on the used die from the new rolls will be unrepresentatively high. The new rollers with a hardened surface will rapidly wear down the softer metal in the die, particularly the raised areas at the edges of the concave die surface. Unfortunately, these roll exchanges occurred in the latter half of production and did not leave any production period sufficiently long (>91 Mg or >100 tons) to resume measurements.

The combination of surface abrasion and metal loss machining the die (two occasions) resulted in a reduction of 15 mm (9/16 in.) in the die thickness over the course of the project. About one-half of this loss was estimated to have occurred in the returning operations.

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This increased the inside die diameter from 762 mm (30 in.) to 792 mm (31-3/16 in.) and put the working surface at the limit of the outward adjustment range of the rolls (particularly with worn and thus smaller diameter rolls). The rolls could no longer be brought down tight against the die and, thus, the frequency of jamming increased.

Due to the reduction in die thickness, the pellet hole length was reduced from 101 mm (4 in.) to 86 mm (3-3/8 in.). The depth of the original inlet taper was reduced even more to only 25% of the original length. The substantial change in the pellet hole configuration from the original would be expected to affect both the densifier performance (power consumption and throughput) and the pellet properties (pellet density). While measurements of performance changes were not made in sufficient numbers or reliability to show any change, the decrease in pellet densities (means) for Configurations 1 and 2 (Table 4) indicates a reduction in pellet density over the course of the die life.

Projected Die and Roller Life

In summary, experience has indicated that the 13 mm (1/2 in.) and 33 cm (13 in.) rollers had reached the ends of their useful life after roughly 1,050 Mg (1,170 tons) and 550 Mg (610 tons), respectively; deteriorating performance (increased frequency of jams) was an indicator in both cases. However, direct use or extrapolation of these figures for any other installation or feedstock is not recommended because of the unusual handling and particularly abrasive feedstock in this application. The die had been reground on two occasions and had also been subjected to the higher wear resulting from use with new sets of rolls on four occasions. Similarly, the rolls have been used on two new dies and have, along with the die, been subjected to a feedstock with high levels of inorganic fines. Highlighting the effect of these fines, the manufacturer has suggested that reducing the ash content of the densifier feed from 25% to 10% (the mean ash levels were 26% and 22%, respectively, in the first and second operating period) would double the life of the die and rollers. As a result of lower inorganic fines alone, this could increase die and roller lives to 2,100 Mg and 1,100 Mg (2,313 tons and 1,211 tons), respectively.

Accepting this premise, and assuming normal roller exchange and die regrind cycle, it is anticipated that a die life of 3,200 Mg (3,550 tons) could be expected. These estimates are believed to be reasonably accurate for a low-ash feedstock (10% to 12%), and serve as the basis for estimating maintenance costs in the economic analyses in the last sections of this report.

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SECTION 4

d-RDF PHYSICAL PROPERTIES

OBJECTIVES

The physical properties chosen for measurement were the moisture, ash, bulk density, pellet density, pellet length and fines content. These properties were selected because of their probable relationship to the use of d-RDF as a supplement to coal in stoker-fired boilers. The values of these properties and their relation to the values for coal will help predict and understand results when d-RDF is transported, mixed, and fired in a coal-burning plant.

TEST PROCEDURES

The sampling and analysis procedures for each property measurement are presented in Appendix D.

Underlying the choice of measurement techniques was the intent of replicating the techniques applied to coal, as much as possible, so that the data are comparable. Therefore, the test methods conformed to ASTM procedures where they were available or could be adapted to d-RDF.

EXPERIMENTAL RESULTS

Data collected are summarized in Table 4. As discussed in Section 2 above, key process flow equipment was changed after 270 Mg (297 tons) production; consequently, data collected before this change were segregated from later data to gain an understanding of the effect on pellet properties.

Data for 25 mm (1 in.) diameter pellets were also separately monitored to ascertain any differences from the 13 mm (1/2 in.) pellets. The definitions of the observed physical properties, their sources, controls and relationship to other properties, where discernible, are discussed below.

Plots of the distribution of d-RDF properties from Configuration 1 have been made and previously reported [23]. These

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TABLE 4. SUMMARY OF d-RDF PROPERTIES, AS-PRODUCED

	13 mm Diameter Pellets						25 mm Diameter Pellets		
	Configuration 1			Configuration 2					
	$\bar{x}$	σ	n	$\bar{x}$	σ	n	$\bar{x}$	σ	n
Moisture (%, DW)	19.1	5.4	92	22.9	8.9	40	22.8	5.0	13
Ash (%, DW)	26.6	6.3	93	23.4	4.1	55	22.8	3.9	13
-38/" Fines (%, AR)	N/A	N/A	N/A	14.9	7.1	15	9.8	5.0	10
Pellet Density (g/cm^3)	1.17	0.21	83	1.01	0.45	16	0.86	0.15	7
Bulk Density (kg/m^3 AR)	620	72	69	570	77	49	434	29	10
Mean Length (mm)	17.9	2.6	88	15.9	2.5	15	--	--	--

Notes
$\bar{x}$ = mean of property measurements
σ = standard deviation
n = number of observations
DW = dry weight
AR = as-received

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plots are included in Appendix E for reference. They are instructive in providing a feel for the range and variation of the data about the mean values reported in Table 4.

DISCUSSION OF RESULTS

Moisture

The moisture content of pellets is lower than the moisture content of the corresponding input MSW feed because of losses in primary and secondary shredding and pelletizing. Several concurrent measurements of the densifier feed and products indicate an approximate 5% loss of the moisture in the feed from the densification process alone.

Experience indicated hard, stable pellets can be produced over a broad range of the input moisture. On the low end, some moisture is needed for die lubrication and pellet cohesion. The pellet mill manufacturer suggests a minimum of 12%. While lower moisture may enhance the fuel characteristics and pellet density, it leads to greater friction and increased power consumption. Moisture contents above 30% generally result in a scaly, loose-bound pellet which breaks more easily in handling. It may also contribute to a tendency of the pellets to decompose if stored for long periods of time. (Section 5)

Considering both equipment operations and pellet properties, the preferred moisture is judged to be in the range of from 15% to 20%. By comparison, the moisture content of mid-continental, bituminous coal may average about 3% to 5%. The upper moisture limit of such coal is only 7% to 8% because it is all surface moisture (unless there is a large quantity of fine particles which will hold more moisture by capillarity). However, the pellets were found to hold as much as 130% moisture (dry wt), reflecting their composition (mostly paper) and suggesting care to keep them away from precipitation or surface water during handling and storage.

Ash

The ash content of d-RDF is a combination of the residue of the combustible material and the free inorganic materials. Because the ash content of the combustible portion of RDF is in the range of 6% to 8%, any excess is due to inefficient removal of inorganic material (mostly fines). Note that for the first production period, the mean and variability for ash were higher than for the second period where a screen and a different type of air classifier were employed. (Section 2)

Lower levels of inorganic fines will reduce wear on the secondary shredder and densifier. Also, lower ash contents in

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the fuel (e.g., to approximate coal ash at 3% to 8%) are desirable to maximize heat value and minimize bottom ash handling and the potential for slagging at the boiler. Although not adopted during this project, process modifications, such as trommeling the MSW input or more efficient screening of the shredded fraction, are available means of lowering the ash content of the fuel.

Pellet Density

Pellet density is important to assure proper flow through the storage and feed systems of the stoker boilers. The particle density of coal is of the order of 1.30 g/cc. Table 4 indicates a mean pellet density 10% to 20% below coal.

Pellet density will vary with input waste composition, moisture content and die hole taper. Above average loadings of certain seasonal materials - lawn clippings, leaves, etc. - have been observed to make poorly densified pellets. Above average amounts of other materials, such as plastic or wood, can result in higher pellet densities.

As stated earlier, moisture below 15% tends to produce higher pellet densities, probably as a result of increased friction through the die and thus greater compaction of the feed. Moisture above 30% will reduce friction and result in poorly bound pellets. Die hole inlet taper appears to be the major controller of pellet density. Dies with a range of taper styles and taper angles and depths are available. In practice, the more severe the taper, the more dense the pellet. Note the lower density of the 25 mm (1 in.) pellets compared to the 13 mm (1/2 in.) pellets in Table 4. Alternative dies with more severe tapers are available as a means of increasing the 25 mm (1 in.) pellet density, as discussed in Section 3.

A single 13 mm (1/2 in.) die was used for more than half of the production. Over this period, the die holes were shortened by regrinding and worn by the material to a less severe taper. This reduction in length and taper, as well as the higher moisture would explain the drop in mean 13 mm (1/2 in.) pellet density over the two production periods from 1.17 g/cm^3 to 1.01 g/cm^3 (73 lb/ft^3 to 63 lb/ft^3).

A second 13 mm (1/2 in.) die, with a more severe inlet taper than the first, was used during the later operations. However, continuing mechanical problems with the die and other processing equipment prevented making sufficient observations on the product to make comparisons to the pellets from the old, more moderately tapered holes.

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Bulk Density

High bulk density is desirable to maximize the calorific content per unit volume, inasmuch as coal stokers by which the d-RDF would be fed are volumetric feed devices. For stoker coal, the bulk density ranges from 725 kg/m^3 to 885 kg/m^3 (45 lb/ft^3 to 55 lb/ft^3). Table 4 shows the 13 mm (1/2 in.) pellets to be 15% to 25% less than coal, but with relatively low variances over both operating periods. Such stability is a benefit in maintaining control of volumetric feed to stoker boilers.

The 25 mm (1 in.) pellet bulk density is lower due to significantly lower pellet densities, as discussed above.

In addition to pellet density, bulk density is a function pellet moisture, pellet length, and fines content. Moisture effects have been discussed. As seen in Figure 17, lower bulk density tends to accompany higher fines content. Thus, one method for increasing the bulk density may simply be to screen the pellet product, say at 10 mm (3/8 in.) to remove the fines and recirculate them to the densifier.

Fines

The d-RDF fines are arbitrarily defined as -10 mm (-3/8 in.) material in the d-RDF product instead of the -6 mm (-1/4 in.) used with coal. This conservative definition was thought more inclusive of single-thickness paper flakes or particles in d-RDF. From the standpoint of increased bulk density, improved material flow, less bunker hangup and reduced dusting, a low fines content is preferred. However, as with coal, some fines are desired to achieve a mix of suspension and on-the-grate combustion in the boiler. Table 4 indicates average d-RDF fines are somewhat lower than the 20% to 40% range typical of coal. It should be noted, however, that many single-thickness paper flakes of 13 mm (1/2 in.) or 25 mm (1 in.) pellet diameter would not be measured as fines by the screening technique used here but will behave like -10 mm (-3/8 in.) particles, making effective fines content somewhat higher. Also, note that these measurements were taken on the as-produced pellets, and any abuse during transport, storage and feeding will increase the level of fines observed in the fuel as it is fed to the boiler.

Fines have been observed traceable to several sources. During pelletizing, certain input materials, such as textiles and some plastic pieces bond poorly. Pellets break at these weak points liberating flakes of these and other materials. Loosely bound pellets, such as those with high moisture, lose an inordinate amount of flakes and chips in handling. Data plotted in Figure 18 seem to support observations correlating high fine content with low pellet density.

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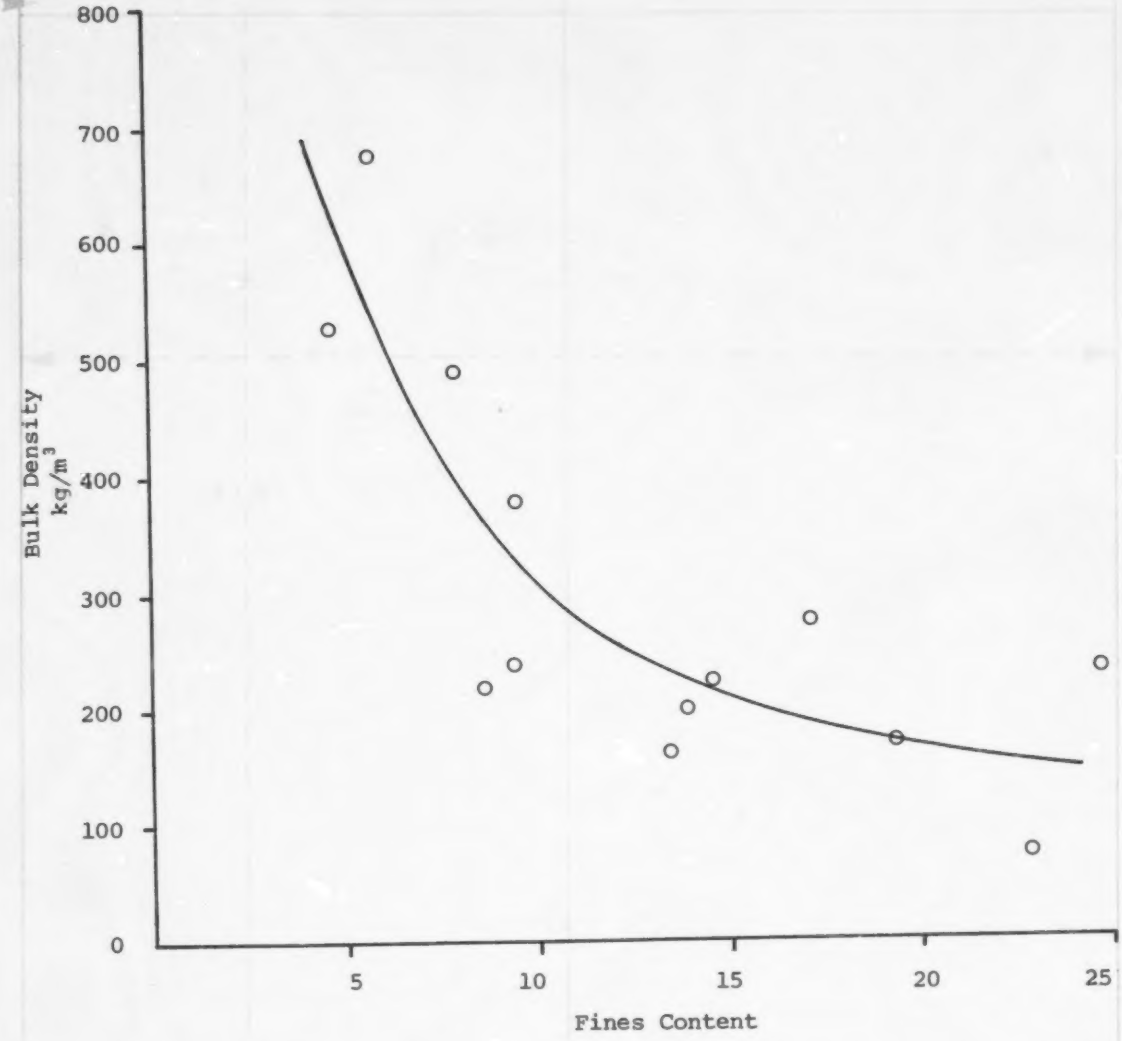

Figure 17. Bulk density versus fines content.

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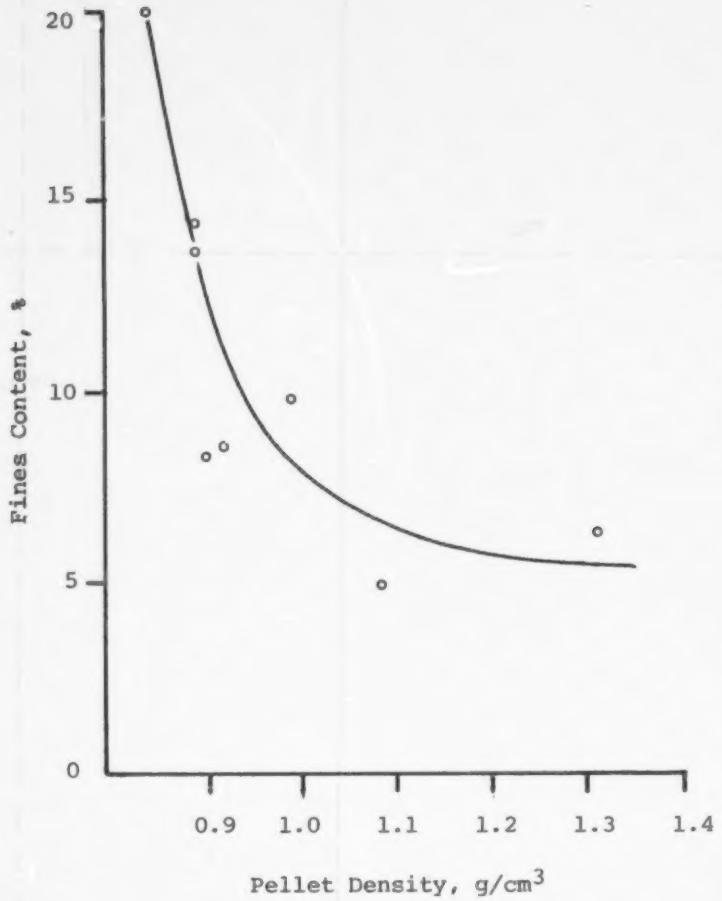

Figure 18. 13 mm Pellet density versus fines content.

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Other fines result from undensified flakes from the size reduction of the nominal 19 mm (3/4 in.) secondary shredded, feed material as it is sheared in the process of being extruded through the 13 mm (1/2 in.) holes. The lower fines content of the 25 mm (1 in.) pellets correspondingly reflects reduction in these fines as the larger opening shears less of the 19 mm (3/4 in.) feed.

It is important to note that fines in the densified product can be easily controlled, and in fact, routinely are in most pelletizing operations, by screening the pellets as they are produced. At ETEF, however, no provision was made for screening the pellets.

Pellet Dimension

Pellet diameter is determined by the diameter of the die openings. Neither the 25 mm (1 in.) nor 13 mm (1/2 in.) pellets as-produced varied by more than ±0.3 mm (±0.01 in.).

Pellet lengths were limited by the position of a breaker bar installed on the interior surface of the cover of the die. The centrifugal force from the rotating die and impacts from loose pellets within the shell cover of the die, however, cause the pellets to break off from the die at random, shorter lengths. Also, as described above, plastics and textiles form shear planes, across which a fracture is likely.

The length distribution of 13 mm (1/2 in.) diameter pellets was observed to lie between 10 mm (3/8 in.) to 19 mm (3/4 in.). Table 4 shows fairly consistent mean lengths from the two production periods. Inasmuch as d-RDF will supplement coal of preferred size (6 to 30 mm or 1/4 in. to 1-1/4 in.) in stoker-fed boilers, this replication is important for maintaining consistent flow through the feeder and distribution of fuel on the grate.

The procedure used at ETEF for measuring pellet length is given in Appendix D. Figure 19 compares two independent measurements of the same pellet population by NCRR and Systems Technology Corp. (Systec); laboratory technicians at Systec used an alternate technique of observing pellet length against a grid marked in 3 mm (1/8 in.) increments. The purpose was to compare the technique of observing length against that of directly measuring each pellet. The compared results show the grid technique to indicate a 10% greater length than the direct measurement technique. This is probably attributable to the uneven end profiles characteristic of the pellets. While a precise length distribution may not be significant in itself, the results suggest a standard procedure is necessary if the data from two sources are to be comparable. From this experience, it appears that the test using the grid procedure was easier to apply.

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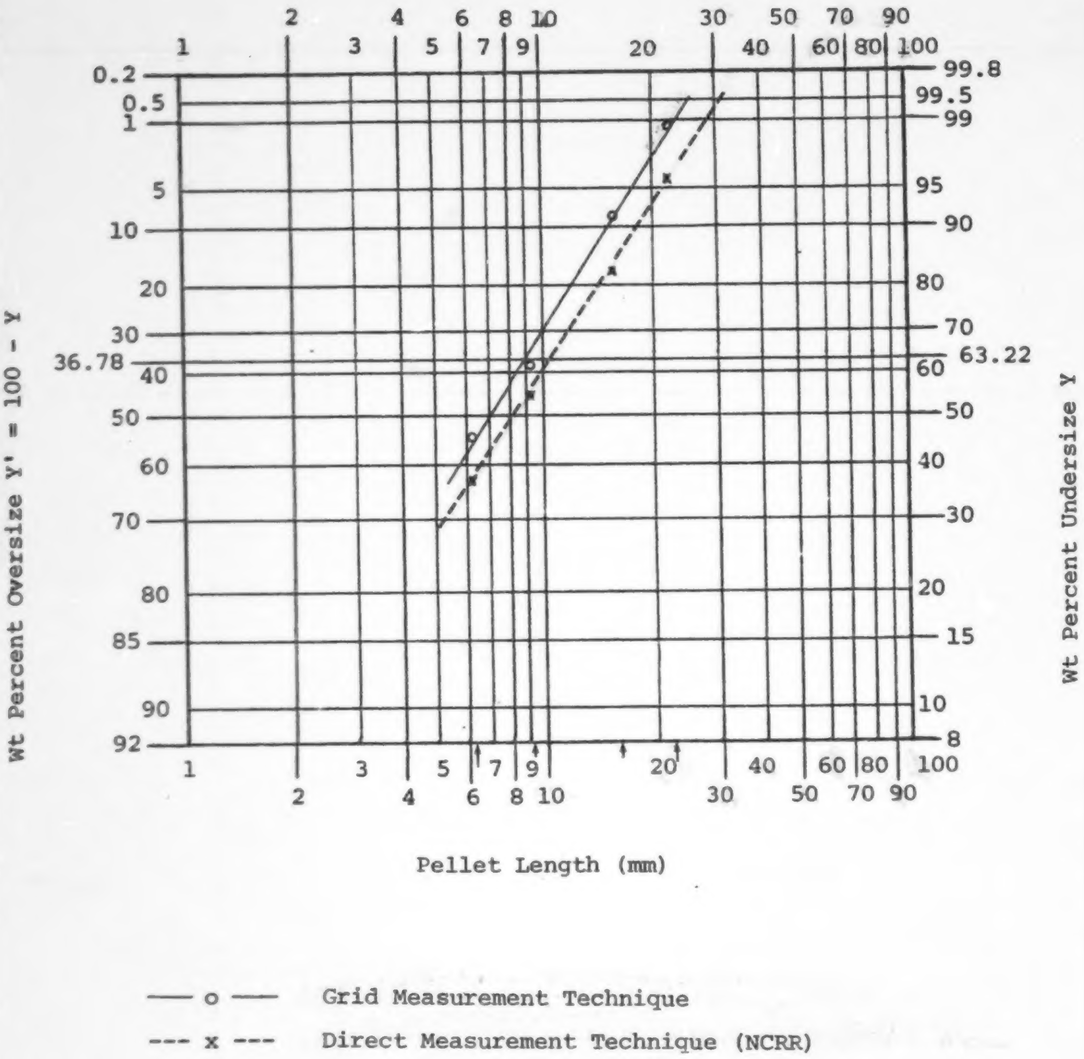

Figure 19. Two independent length measurements of same pellet population.

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Integrity

Integrity of d-RDF can be defined as its ability to maintain stable dimensions and other pellet properties during transport, storage, feeding and other handling. This is important once bounds have been established so that any changes in pellet properties may be predicted.

Properties affected by immediate, as-produced handling are primarily pellet length and the concomitant fines content. To evaluate the relative amount of abuse pellets can withstand without losing integrity, a drop/shatter test (Appendix D) was adapted from a test for coke (ASTM D 3038-72). In this procedure, pellets are abused by being dropped on a steel plate from a six-foot height. Drop/shatter tests were run on 13 mm (1/2 in.) and 25 mm (1 in.) pellets from production and from samples of pellets from the storage yard. Typical before and after distributions are shown in Figures 20 through 22.

For the as-produced 13 and 25 mm (1/2 and 1 in.) pellets, Table 5 shows no significant mean length change (t test) or variation in standard deviation (F test). Curiously, the distribution shifted significantly (χ^2 test) indicating skewing of the distribution. Looking at Figure 20, both symmetic and asymmetric breaking of larger pellets seem to be occurring. Although only two tests are reported on the as-produced pellets, the absence of significant breakage was observed on a significant number of trials. This led to increasing the number of drops from 2 to 4 to 10. Data still indicated no significant changes in mean length, but a steady increase in fines (Figure 21). Apparently, after a certain level of abuse, most weak pellets have broken, and further abuse simply chips pieces from the pellet ends.

A test on Sample D with over 30% moisture content revealed a greater susceptibility to breakage when going from two to ten drops. The before and after distribution is shown in Figure 22. The result would be expected.

The length distribution and fines content of the pellets have been monitored through handling and storage to assess the changes that may occur. The data from this investigation are reported in Section 5.

It should be mentioned that an integrity control practice employed by the animal feed industry is the immediate cooling of as-produced pellets. This technique results in a harder pellet which holds its integrity longer. Cooled d-RDF has been observed to harden as well. This practice might be considered for integration into a full-scale d-RDF facility.

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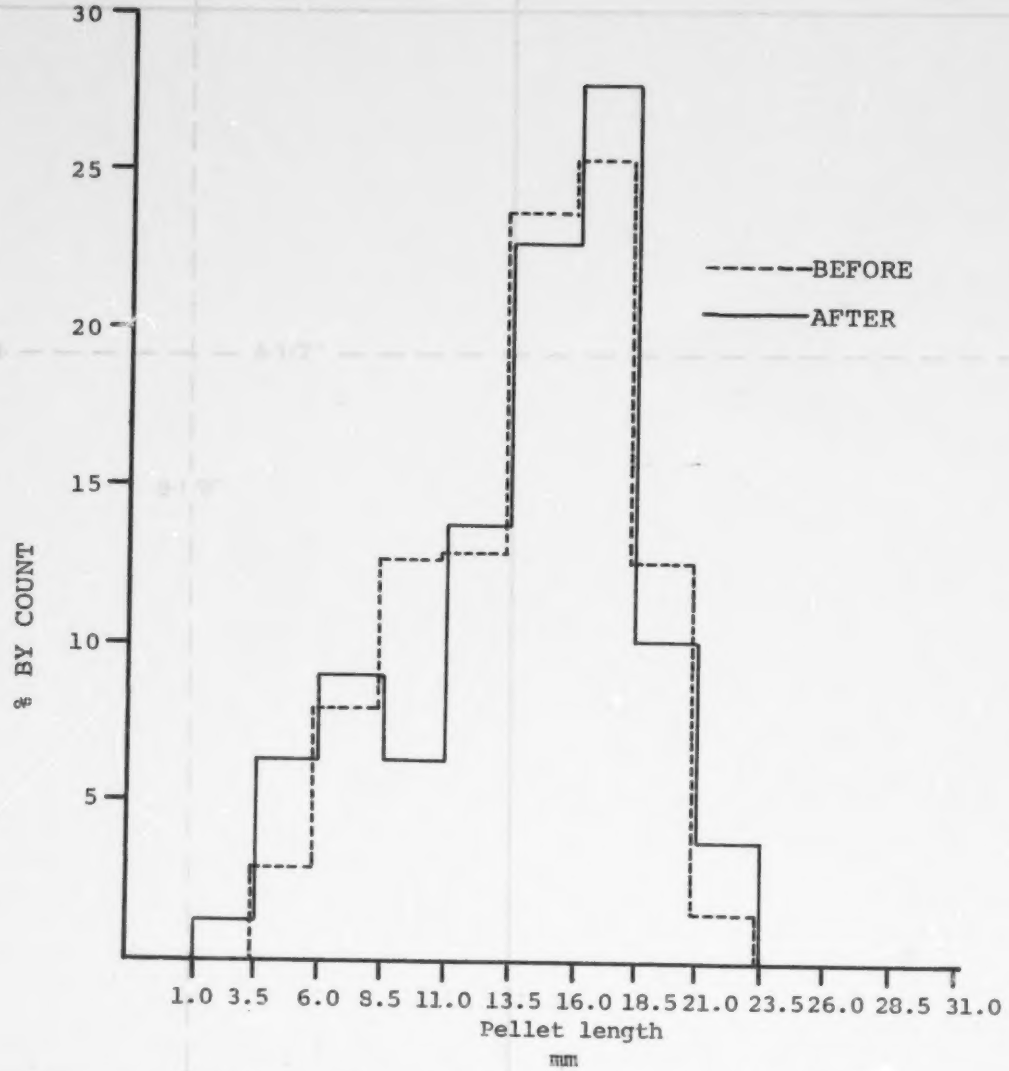

Figure 20. Pellet length distribution, sample A, 13-mm diameter as-produced, 2 drops.

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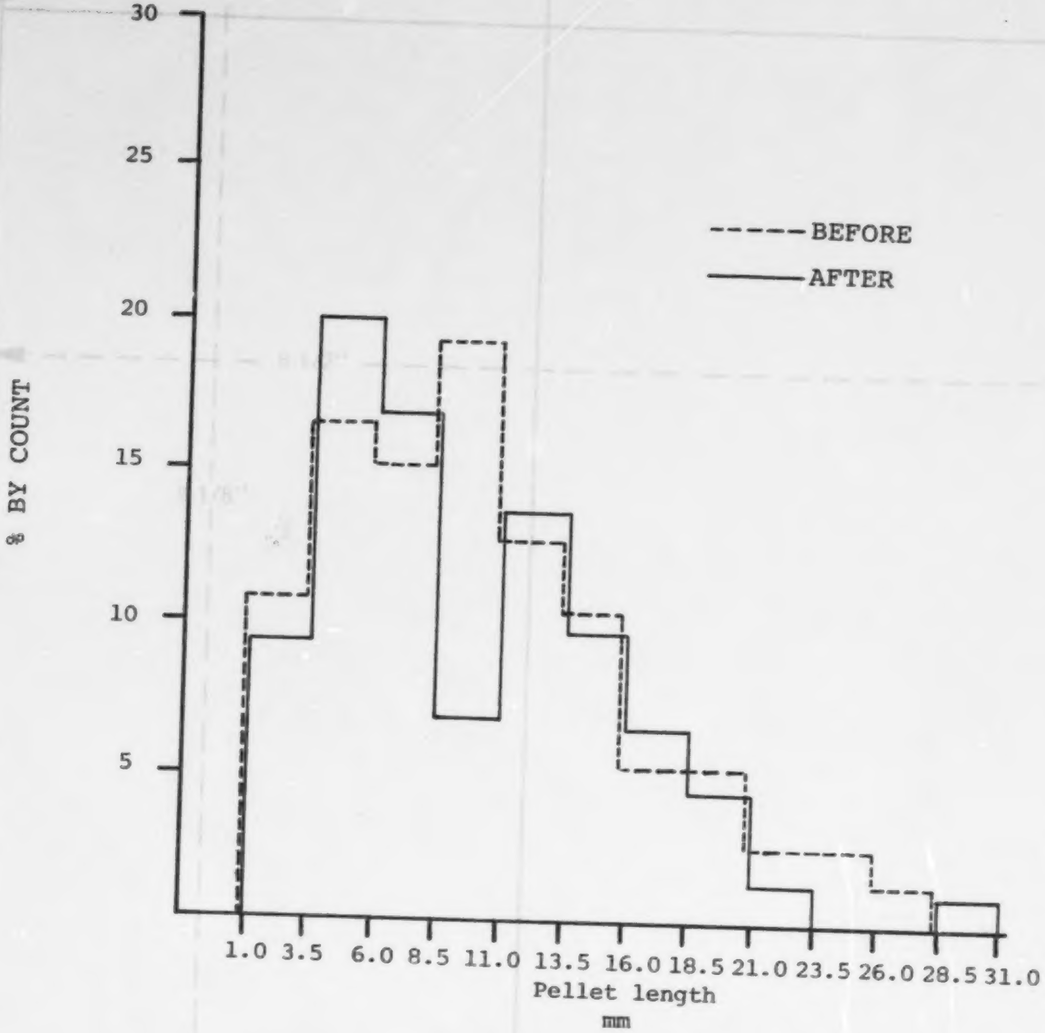

Figure 21. Pellet length distribution sample C, 13-mm diameter storage yard, 10 drops.

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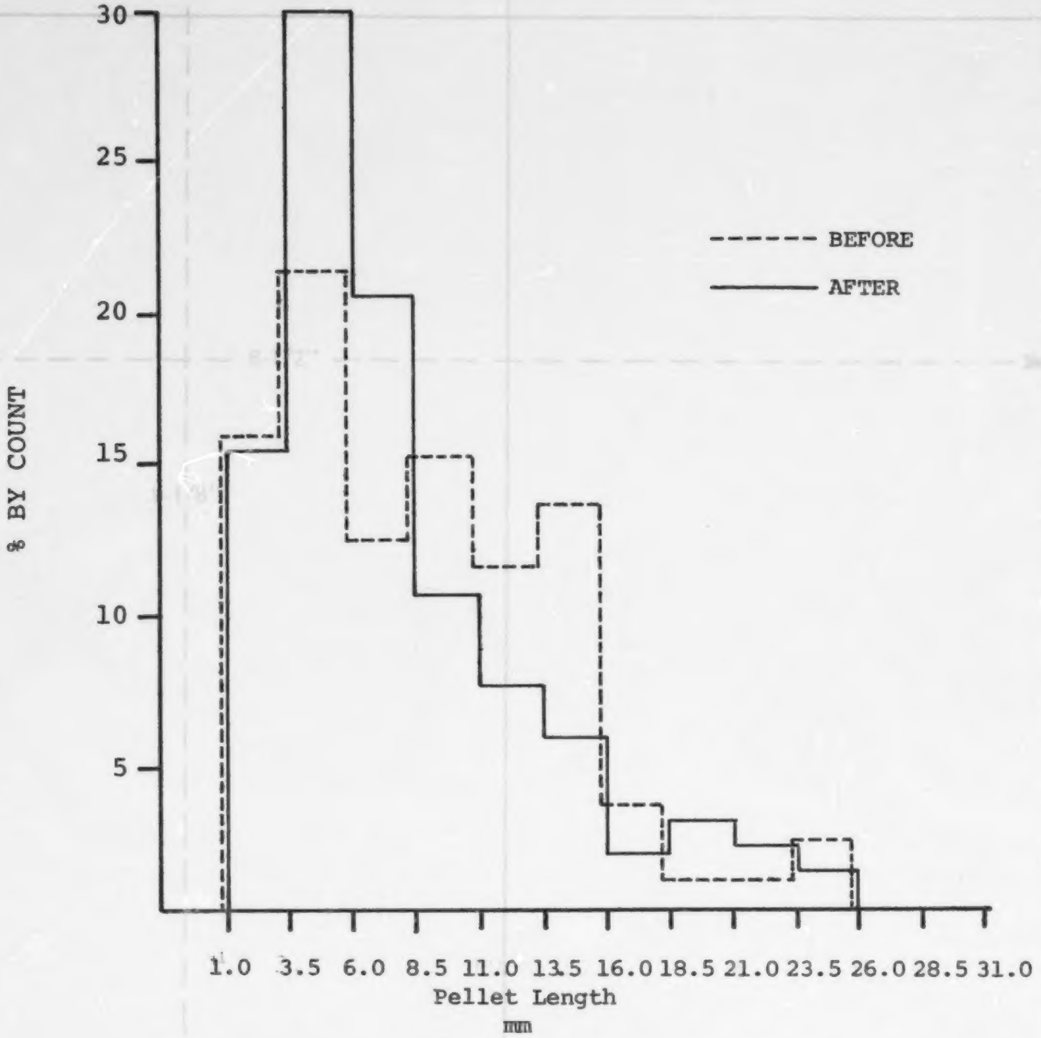

Figure 22. Pellet length distribution, sample D, 13-mm diameter storage yard, 10 drops.

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TABLE 5. DROP/SHATTER TEST RESULTS

Tests of Distribution:

Variance ratio (F test)
Means (t test)
Distribution (x^2 test)

Sample	Description	Percent Moisture	Test F	Test t	Test x^2	Mean Length (mm)	% Fines
A	13 mm as-produced	11	-	-	-	14.31	9.8
	2 drops		*	*	**	14.25	10.0
B	13 mm as-produced	21	-	-	-	11.50	11.5
	2 drops		*	*	**	10.35	12.0
C	13 mm storage yard	15	-	-	-	10.28	17.9
	2 drops		*	*	**	9.32	22.1
	4 drops		*	*	*	9.38	24.2
	10 drops		*	*	*	9.59	25.6
D	13 mm storage yard	34	-	-	-	6.90	N/A
	2 drops		*	*	**	5.98	N/A
	10 drops		*	**	**	5.46	N/A

*Hypothesis of no change accepted at 95% level of certainty

**Hypothesis of no change rejected at 95% level of certainty

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The relationship of this test procedure to the loss of integrity in actual handling is unknown. Observations during the production, transport and storage indicate resistance to abuse to be a function of pellet density, moisture content and pellet temperature. Low density pellets tend to have partly separated shear planes and ragged edges that make them more susceptible to breakage. Pellets with higher moisture contents, as a result of moisture in the feedstock or moisture adsorbed in storage, tend to swell and delaminate and are more easily broken. Pellets that are not cooled after production or are subjected to higher temperatures in storage were observed to be less cohesive and, thus, more easily broken.

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SECTION 5

STORAGE AND HANDLING

Storage of the d-RDF was required during the course of the production program to permit accumulation of a sufficiently large quantity for use in the test firings. Slowdowns in production and delays in identification of the site for the combustion tests required additional handling and repiling of the material to gain more storage space. The storage period was extended to over 12 months - significantly longer than anticipated. During the latter part of this period, smoldering seams of pellets surfaced and ignited the plastic cover and tire anchors. These events and possible causes will be discussed after a description of the storage site and evaluation program.

STORAGE SITE DESCRIPTION

An outdoor site of 930 sq meters (10,000 ft^2), 7 km from the production site was selected for pellet storage. Although an indoor site was preferred, considerations of fire liability, costs and schedules precluded it from consideration. The required area was estimated from projected tonnages, bulk density, and a pile height of six feet (as prescribed for lignite coal). Allowances were also made for vehicle maneuvering. The location was accessible by tractor trailers and adjacent to a rail siding.

The surface was graded and asphalted to segregate the pellets from the soil, aid equipment mobility, and provide proper drainage. Access to the site was limited by a peripheral chain-link fence, and the entire pile was covered with a plastic tarpaulin anchored by tires.

A plan was developed to monitor the impact of storage on site locality and pellet properties. The plan involved:

(1) placement of samples with known properties to track material condition;

(2) temperature monitoring;

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(3) random sampling and observation of pellets during repile and transfer operations; and

(4) observations on environmental and health impact of biological activity, odors, dusting, etc.

Observations on environmental health aspects of storage concerned presence of rodents or other vectors; whether the decomposition of d-RDF would generate offensive odors; whether the stored d-RDF would be a source of microbiological aerosols and other dusts; and presence of liquid effluents from the pile.

No problems with vectors were experienced during storage. Presumably, the highly cellulosic content and pelletized form of d-RDF make it less attractive as a food supply. Although a variety of grubs, spiders and other crawling insets were found - especially during warmer months - in the opinion of a consulting entomologist they were no greater in number or identity than might be found in ordinary soil. Fly concentration was observed to be within usual ambient levels; qualitative observations at ETEF suggest that fly larvae in MSW are removed or destroyed by screening or densification. Fungi grew on certain moist surface areas of the d-RDF, but not in significant amounts.

9-1/8"

Odors generated by stored d-RDF were notable only when the covers were removed or the pile excavated. The strong, compost-like odors were still not as strong as decomposing, unprocessed solid waste. In addition, odors were moisture- and location-specific, with drier pellets and surface pellets being less pungent. These differences may be traceable to differences in rate and form of decomposition. Reduced moisture inhibits the growth of microorganisms and hence reduces the rate of decomposition. At some of the exposed surfaces of the pile, conditions existed for aerobic decomposition; interior conditions would favor anaerobic decomposition which yields gases producing some of the more noticeable odors.

Dusting was no problem when the pile was covered, but during handling, flakes blown from dry, broken pellets did create a minor off-site dusting.

The plastic cover and graded surface effectively prevented rain from percolating through the pellets, except at occasional open seams or holes in the tarp. There was no observed discharge of water effluent from the pile.

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STORAGE TEST DATA

To track the condition of the material at different locations and durations of storage, several tests were devised. Originally, five-gallon plastic drums were perforated and filled with d-RDF. They were later found to be prone to damage during handling and, because they were rigid and relatively closed, did not provide conditions representative of the actual pile. Flexible plastic 6 mm (1/4 in.) mesh bags were later substituted. They were filled with pellets of known characteristics and were spotted at various locations in the pile and later retrieved and analyzed for change. Properties analyzed included moisture content, ash content, mean length and fines. Temperatures in the pile, at the vicinity of the bags, were measured.

The bagged samples were planted in areas of pellets from the same production period. Locations are shown in Figure 23. As the side profile shows, depths were based on the original 2 m (6 ft) pile height, approximately 0.3 m (1 ft) and 1.3 m (4 ft) from the bottom and 0.3 m (1 ft) from the surface. Some samples were lost in unprogrammed repiling and excavation, which will be discussed.

Data before and after planting for several bagged samples are summarized in Table 6. While scattered moistures and general lack of correlation between properties and locations reflect the observed random pile dynamics, a trend toward deterioration with storage is evident. After five weeks, decrease in mean length is slight, as was the increase in fines. The fines values below the as-received level reflect variations in sampling and measurement. Much lower mean lengths after 21 weeks suggest real fines increases with longer storage.

Temperature measurements were made at the same points on average intervals of two weeks. Figure 24 provides the results of the probing over a 20-week period in terms of the means and standard deviations. Temperature patterns were random, with little apparent relation to location or age of material. The significant variation at single points, with changes up and down from one period to the next without apparent cause was not understood until later excavations. But the fact that the highest individual reading during the first 10-month period was 70°C (150°F) at the time gave no cause for alarm for spontaneous combustion in the pile since biological decomposition is known to be self-limiting at about this temperature.

Seven months into the production effort with about 600 tons in storage, the height of the pile was increased in some areas from 6 ft up to 10-15 ft. This was necessary to make additional room for storage due to larger than estimated volume requirements and delays in transport of the pellets out of storage to the test burn site.

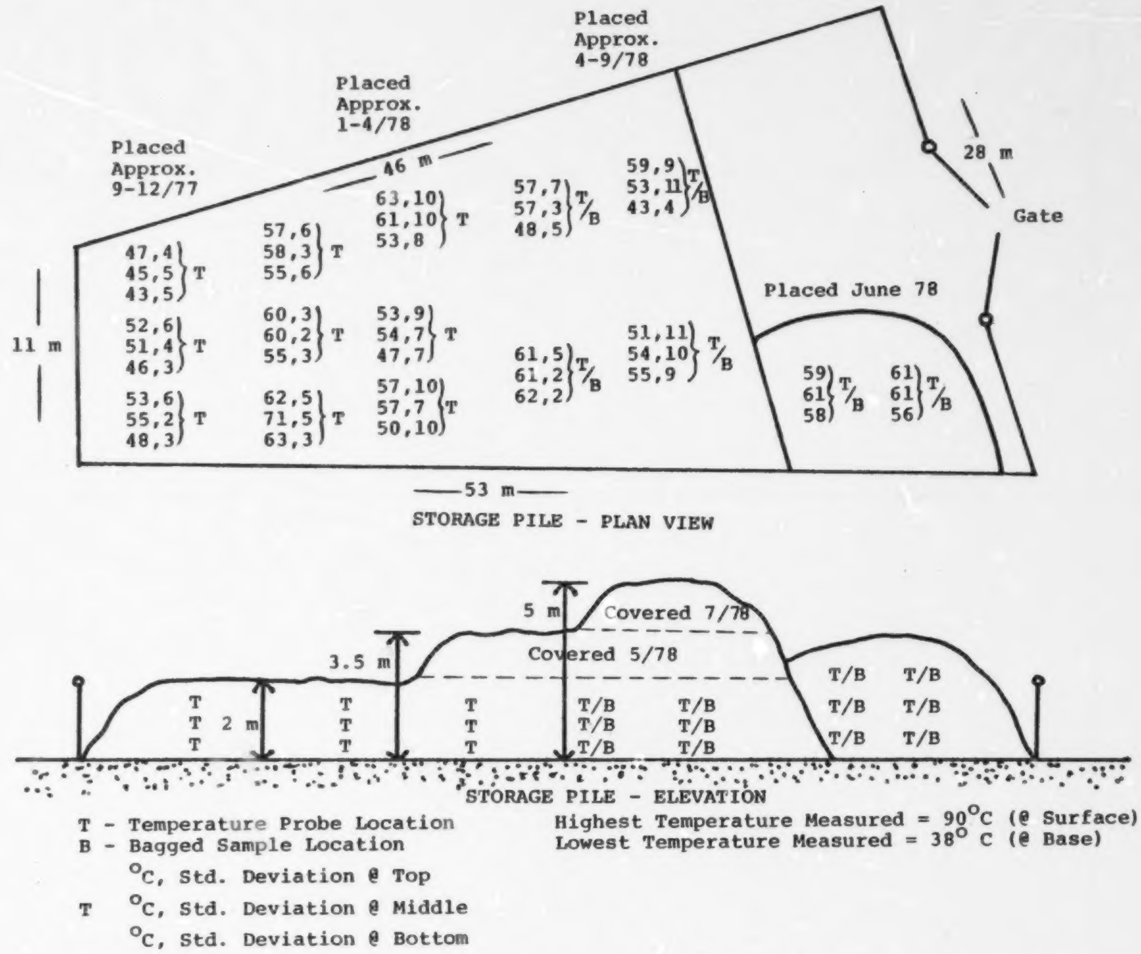
Placed Approx. 9-12/77
Placed Approx. 1-4/78
Placed Approx. 4-9/78
Placed June 78
46 m
28 m
Gate
11 m
53 m
47,4 45,5 43,5 T
57,6 58,3 55,6 T
63,10 61,10 53,8 T
57,7 57,3 48,5 T/B
59,9 53,11 43,4 T/B
52,6 51,4 46,3 T
60,3 60,2 55,3 T
53,9 54,7 47,7 T
61,5 61,2 62,2 T/B
51,11 54,10 55,9 T/B
53,6 55,2 48,3 T
62,5 71,5 63,3 T
57,10 57,7 50,10 T
59 61 58 T/B
61 61 56 T/B
STORAGE PILE - PLAN VIEW
2 m
3.5 m
5 m
Covered 7/78
Covered 5/78
T
T/B
STORAGE PILE - ELEVATION
T - Temperature Probe Location
B - Bagged Sample Location
T °C, Std. Deviation @ Top
°C, Std. Deviation @ Middle
°C, Std. Deviation @ Bottom
Highest Temperature Measured = 90°C (@ Surface)
Lowest Temperature Measured = 38° C (@ Base)

Figure 23. Storage pile layout, temperature probe data and sample location.

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TABLE 6. SUMMARY - d-RDF STORAGE EFFECTS: BAGGED SAMPLES

Place/Recovered		Duration in Storage	Moisture	-3/8 Fines	Mean Length	Ash
		Weeks	% dry wt.	% dry wt.	mm	% dry wt.
Placed 4/26/78		-	35%	10%	13.5	23.5
Recovered 5/31/78	Top (L)	5	28.2	12.5	12.3	23.1
	Top (R)	5	25.4	11.2	12.9	21.0
	Middle (L)	5	11.5	9.6	12.2	22.5
	Middle (R)	5	50.0	14.3	11.9	21.7
	Bottom (L)	5	20.0	9.0	11.3	24.1
	Bottom (R)	5	10.2	17.0	9.5	22.0
Placed 4/4/78		-	15.5	6.7	16.8	20.3
Recovered 8/28/78	Top (L)	21	4	8	10.8	22.0
	Middle (L)	21	32	7	11.3	23.0
	Bottom (L)	21	57	27	8.8	25.0

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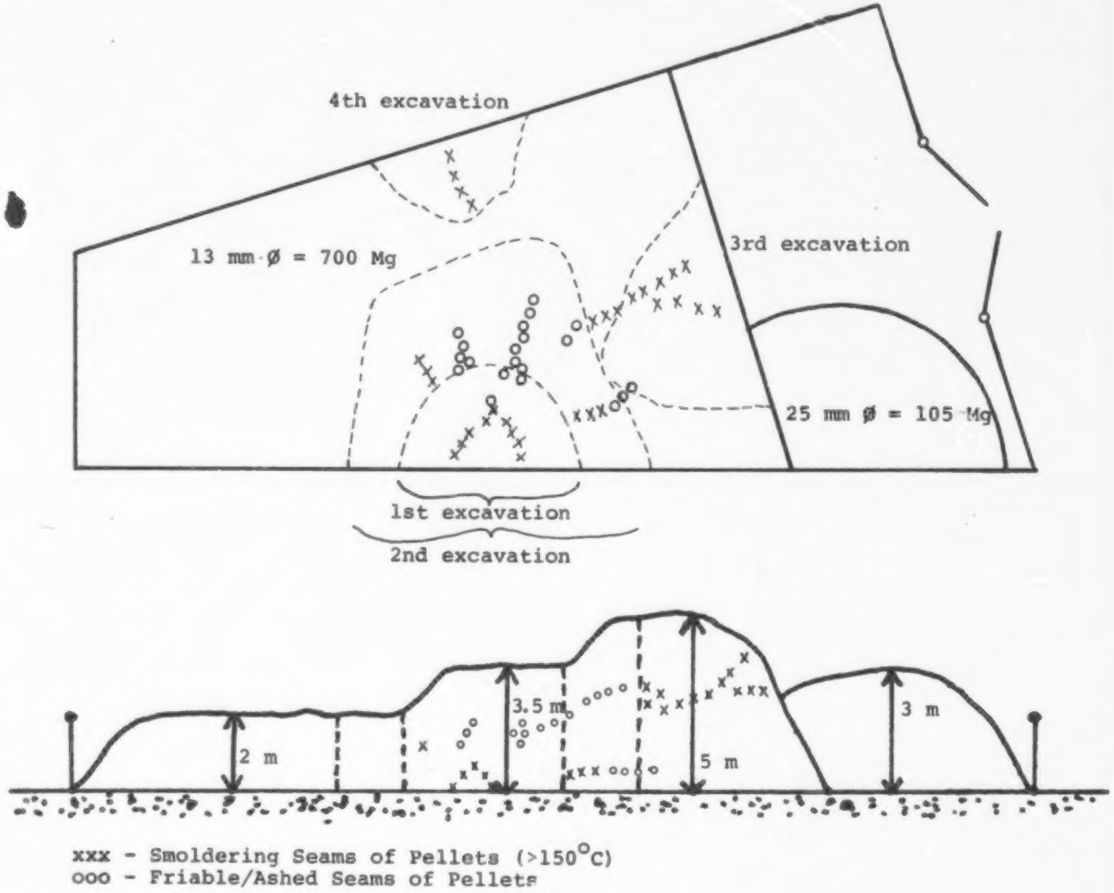
4th excavation
13 mm Ø = 700 Mg
3rd excavation
25 mm Ø = 105 Mg
1st excavation
2nd excavation
2 m
3.5 m
5 m
3 m
xxx - Smoldering Seams of Pellets (>150°C)
ooo - Friable/Ashed Seams of Pellets

Figure 24. Oxidized pellets and storage pile excavations.

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Some 300 tons were repiled over the top of an existing section as profiled in Figure 24.

PELLET OXIDATION

Late in the first summer after 10 months into storage, a series of smoldering seams of pellets with temperatures above 150°C (300°F), the limit of the temperature measurement probe used on the site, and hot enough to ignite the plastic cover and tires, surfaced in an area where the pellets had been repiled. (Note Figure 24.) The pellets themselves did not ignite, probably because of close packing and lack of oxygen on all sides. Excavations to trace and extinguish the hot seams began immediately.

These smoldering seams surfaced on four other occasions over the next two months at widely separate locations around the pile. Each time the affected area was excavated to a depth that the smoldering seams dissipated. The excavated material was drenched with water with the resultant degradation so bad that the pellets could not be used later in the test firings. Some 500 tons was thus lost. Although efforts were made to keep water off the remainder of the pile, some rainfall or water from fire hoses undoubtedly added to the moisture content and accelerated degradation of the d-RDF product which was shipped to the burn site.

Excavations and measurements of the affected areas, shown in Figure 25, provided some insights but no conclusive explanation as to the cause. Whereas the as-produced pellet moisture had varied from only 15 to 35%, pellets with from 4 to 131% (dry weight) moisture were uncovered. They ran, for the most part, horizontally through the pile at varying depths. They averaged only 100 cm (4 x 4 in) cross-section. The hot, smoldering seams were also randomly placed, often not connected, and adjacent to both very wet and very dry material. The mulch smell, darkened color and increased levels of fines in many other parts of the pile indicated that composting was occurring. The smoldering, charred seams extended back into portions of the pile that were still at the original six-foot depth but were more extensive in the repiled portions. The affected pellets were black and brittle, presumably partially oxidized or pyrolyzed.

These incidents raise questions as to the cause and to what extent the particular production, handling and storage techniques may have contributed to the problem. Exact predictive schemes are impossible to develop for such heterogeneous material. Hot and humid weather, lengthy storage, repeated handling, water penetrating through seams or breaks in the cover, and the retention of the moisture and heat by the cover

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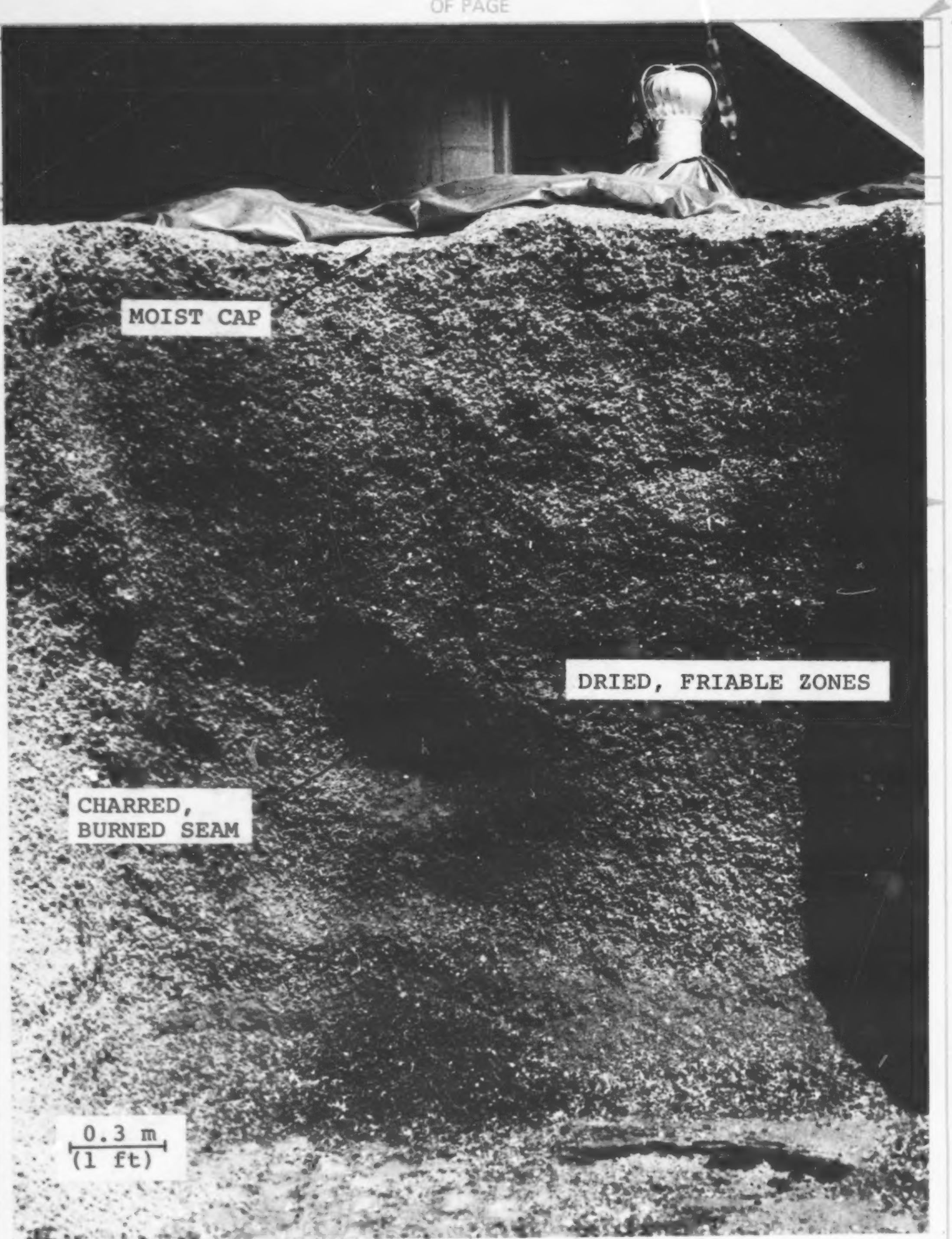
MOIST CAP
DRIED, FRIABLE ZONES
CHARRED, BURNED SEAM
0.3 m
(1 ft)

Figure 25. Excavation of storage pile and smoldering seam of pellets.

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must all be considered. Conjecture is that the exotherm of biological decomposition (composting) provided a sufficient rise in temperature to trigger a chemical reaction, probably of an oxidant in the waste. A subsequent higher exotherm from chemical oxidation of the pellets raised the temperature further. These hot seams would dry adjacent pellets and then begin, in turn, to oxidize them. The d-RDF was made from household wastes, and portions may have contained an oxidant in the form of nitrates in fertilizer, for example.

A comparison of mean pellet property data from samples during production to samples after storage is presented in Table 7. The results are in agreement with trends suggested by observations and bagged samples. Moisture and fines contents increased markedly, and varied much more widely (larger coefficient of variation) than the as-produced pellets. This reflects the random levels of moisture and decomposition observed throughout the piles.

The length and bulk density decreased. Exposure to wet/dry cycles is known to "puff" pellets. With bonds weakened, the pellets break more easily, liberating quantities of fines. After a certain level of abuse, however, most weak pellets have broken and further abuse simply chips pieces from the pellet ends. These observations would explain the wide range of fines, yet more stable mean lengths and densities.

Throughout storage, ash contents remained comparable to as-produced levels, as would be expected.

MATERIAL HANDLING AND TRANSPORT

During excavation of the pellets from the storage pile, it was observed that the pellet pile would maintain stable perpendicular walls (90° angle of repose) up to the full 5 m (15 ft) height. However, when the material was handled, there was little secondary agglomeration or clumping apparent. When a section was dug out and repiled, it would assume the free-flowing characteristics of the fresh material with a similar angle of repose (35° to 37°).

Thirty cubic meter (40 yd^3) aluminum dump trailers with tie-down tarp covers were used for the 360-mile trip to the test burn site in Erie, Pa. The material loaded out at an average density of 400 kg/m^3 (25 lb/ft^3) with little settling during the trip. Aside from considerable dusting during loading of the trailers, there were no problems with material agglomerating, freezing, sticking or other handling problems observed during the transportation of the pellets.

TABLE 7. SUMMARY OF d-RDF PROPERTIES AS-PRODUCED AND AFTER STORAGE

	As Produced			After Storage		
Item	$\bar{x}$	CV.,%	n	$\bar{x}$	CV.,%	n
Moisture (% DW)	22.9	35.8	40	43.9	89.3	27
-3/8" Fines (%, AR)	14.9	47.7	15	28.1	88.8	27
Bulk Density (kg/m^3 AR)	575	13.3	49	410	13.6	28
Mean Length (mm)	15.9	15.7	15	9.8	12.7	19
Ash (% DW)	23.4	17.5	55	23.4	7.7	13

Notes

DW = dry weight

AR = as-received

$\bar{x}$ = mean of property measurements

CV = coefficient of variation $\frac{\bar{x}}{\sigma}$

n = number of observations

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The earlier observations on material handling characteristics at the Washington storage site conflict with experiences with the same material after two-three months storage at the test burn site (Erie, Pa.) where agglomeration and clumping occurred. This may be due to a change in material properties over time, may be a result of shipping, or reflect impact of storage in a much colder winter climate. The complete results of storage, handling and feeding at the boiler sites will be discussed in a separate report [11].

CONCLUSIONS AND RECOMMENDATIONS

The problems with deterioration and oxidation during storage, as experienced here, are believed to be related to cover design, multiple handling and length of storage. Based on these observations and data collected, recommendations toward improved d-RDF storage design and handling techniques can be made.

Use of a Ventilated Covering Such as in Agricultural Silos or Indoor Storage

The primary benefit would be to dissipate heat and moisture from the pile, while protecting the pellets from weathering. The lower moisture content would inhibit generation of heat and odors by slowing the decomposition rate. Less heat, both from within and without the pile, minimizes the possibility of triggering chemical reactions and oxidation hazards.

Control Length of Storage

Over a period of four to eight weeks, it is unlikely that significant biological activity or pellet degradation would occur, particularly with a correctly designed storage facility and retrieval plan (first in, first out). Monitoring of the storage pile to try to detect and predict material conditions does not appear fruitful because of the dynamics and randomness of the conditions in the pile.

Minimize Handling of the Material

Pellets are subject to physical deterioration each time they are handled, particularly after storage where the temperature and/or moisture may accelerate the biological decomposition by aerating the material and re-distributing moisture throughout the piles.

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SECTION 6

d-RDF SYSTEMS FOR SMALL COMMUNITIES: SUGGESTED APPROACH

This and the last two sections of this study provide a technical and economic evaluation of the densified refuse-derived fuel (d-RDF) facilities for small communities, processing up to 200 Mg of municipal solid waste per day.

Section 6 will examine the elements of a possible approach and outline the approach taken. The following, shorter sections deal with the layout and costing of a small facility, and with its economic viability for given sale prices of energy and landfill cost avoidance.

Small communities can ill afford the capital investment and operational and managerial complexities of high technology, capital-intensive resource recovery systems tailored to the needs of large metropolitan areas (1000 Mg of waste or more per day). The relative cost of scaling down and the requirements for a variety of skilled labor might be perceived as potentially serious impediments.

The objective of this study is to evaluate, on technical and economic grounds, one possible approach to resource recovery in a small community plant (100 to 200 Mg/day [110 to 220 ton/day]), based on the production of d-RDF. Generally, such a d-RDF fuel would be used as a supplemental fuel to particle coal in stoker-fired boilers. Thus it is assumed at the outset that a customer (or customers) has been found and is willing to purchase the fuel at a cost based on energy content for use in a stoker-fired combustion unit.

Based on previous and current work performed at the National Center for Resource Recovery [21,23], realistic projections can be made for the capital, labor and operating and maintenance costs of densifying. Using this information, the question examined here can be approached in reverse order, by asking: how much can be afforded as plant and equipment (other than the densifier) and associated structures (building, etc.) given the required quantity and sales price of d-RDF and the cost of densifying?

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Once the answer is determined, several alternate RDF production schemes are explored that might fit the economic and technical constraints.

Finally, a preliminary layout and price range is developed for a typical system likely to meet the needs of small communities. The cost to build the facility will be compared to the projected front-end capital available for varying fuel values and alternate disposal costs.

COST OF DENSIFICATION

Cost projections are made here for the capital, operating and maintenance costs for a densification subsystem to receive a processed feedstock and produce a densified product. The layout and costing of both the densifier and predensification processing represent significant changes from a pilot system evaluated by NCRR over two years of operation and 1275 Mg (1,400 tons) of production. The reader is directed to Sections 1 to 5 of the present report for a complete discussion of these experiences.

In summary, the changes are as follows:

(1) Utilization of screening in the predensification processing to remove glass and other inorganic fines, thereby reducing wear and improving pellet integrity and fuel properties.

(2) Selection of the size reduction equipment to obtain positive particle size control, particularly on the textiles fraction of the waste stream.

(3) Use of a die with 25 mm (1 in.) holes, rather than 13 mm (1/2 in.) holes as used in the experimental program, to reduce tendency for jamming.

(4) Addition of a screen and cooler for the d-RDF product to remove unpelletized fines and harden the d-RDF by cooling.

Figure 26 is a schematic showing the equipment arrangement for a densification module with one or two densifiers. Table 8 summarizes the capacity and the capital, operating and maintenance costs (1979 basis) for both one and two shift operations. The details for the capital cost projections are found in Table F-1 and for the operating and maintenance costs in Table F-2.

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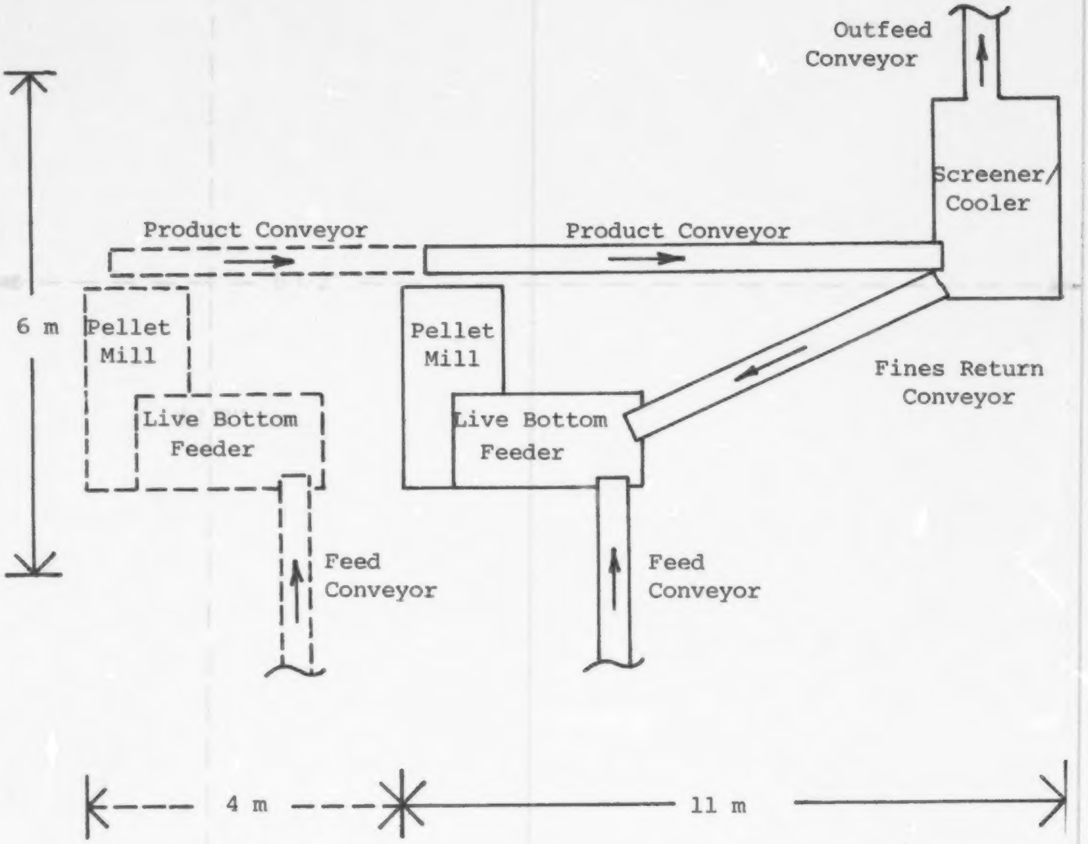
Outfeed
Conveyor
Screener/
Cooler
Product Conveyor
Product Conveyor
6 m
Pellet
Mill
Pellet
Mill
Fines Return
Conveyor
Live Bottom
Feeder
Live Bottom
Feeder
Feed
Conveyor
Feed
Conveyor
4 m
11 m

Figure 26. d-RDF module layout schematic for one or two densifiers.

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TABLE 8. d-RDF MODULE CAPACITY AND CAPITAL, OPERATING AND MAINTENANCE COST SUMMARY*

Item	1 Densifier	2 Densifiers
Capacity		
Module - Hourly 4.5 Mg/h @ 80% avail.	3.6 Mg/h	7.2 Mg/h
Module-1 shift @ 7 h/day	25 Mg/day	50 Mg/day
Module-1 shift @ 250 day/y†	6,300 Mg/y†	12,500 Mg/y†
Module-2 shifts @ 14 h/day	50 Mg/y	100 Mg/y
Module-2 shifts @ 250 day/y	12,500 Mg/y	25,000 Mg/y
Capital cost		
Total cost	$219,700	$389,900
Annual @ 8%/y, 10 years	32,955	58,485
Unit cost for 12,500 Mg/y (2 shifts)	2.64/Mg	-
Unit cost for 25,000 Mg/y (2 shifts)	-	2.34/Mg
Operating cost		
Labor, materials - 1 or 2 shifts	$2.35/Mg	$1.67/Mg
Utilities	$1.28/Mg	$1.28/Mg
Maintenance	$3.91/Mg	$3.91/Mg

*Refer to Appendix F for details.

†Not studied due to poor economics.

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A ring extrusion-type densifier as was used in the production program is suggested here. However, auxiliary equipment, operation and maintenance costs, capacity, and d-RDF properties would not be expected to vary greatly for other types of densifiers. A representative list of densifier manufacturers is provided in Appendix G.

The capital cost in the example includes a conveyor to deliver the feed; a large surge bin with metering screws; a California Pellet Mill (CPM) densifier with two 25 mm (1 in.) dies and two sets of rollers; product conveyors; a pellet cooler and a multi-deck screen for fines removal; conveyors for product loadout and fines recirculation; electrical control enclosure; mechanical and electrical installation costs; a building cost based on allocation of a part of an existing structure; and engineering, freight taxes and contingency costs.

The operating costs include the proportioned time of an equipment operator and power requirements on a unit throughput basis assuming a nominal 3.6 Mg/h (4 ton/h) rate for a single densifier.

The maintenance costs are expressed on a unit throughput basis. They include die rehabilitation (regrinding) or replacement, roller shell (or assembly) replacement and an estimate for the nominal maintenance on the pellet mill drive, conveyors and screens. The presumed maintenance schedule and equipment costs are given in Appendix F.

The capacity of a single densifier with a one-inch die and nominally 25 mm (1 in.) feedstock is projected to 4.5 Mg/h (5 ton/h). Assuming an 80% availability to account for start-up transients, occasional jams and blockages, the realized capacity would be 3.6 Mg/h (4 ton/h).

ALLOWABLE CAPITAL INVESTMENT

This part examines the allowable capital investment, upstream of the densification unit just described, which can be afforded. This is taken to mean that the options of landfilling or processing and densifying should be economically indifferent. The analysis rests on the costs of densification established above and on the following assumptions:

- Pelletizer capacity (nominal): 3.6 Mg/h (4.5 Mg/h @ 80% availability) for one densifier; 7.2 Mg/h for two densifiers.

- Operating time: 2 x 7 hours, 250 day/yr (two shifts).

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- Equipment life: 10 years
- Fuel heating value: 13.94 MJ/kg (6,000 Btu/lb), as-received, or 13.94 GJ/Mg (12 x 10^6 Btu/ton)
- Sale price of fuel: k_f = $1.42/GJ ($1.50/M Btu) or $2.37/GJ ($2.50/M Btu)
- Ferrous sale price (where included): $33/Mg ($30/ton), F.O.B. plant
- Ferrous material recovered: .06 Mg recovered/ Mg of input waste
- Landfill avoidance cost: variable "x" (ranging from 0 to 15 $/Mg)

Table 9 (Parts 1 and 2) present calculations of the front-end available capital (F.A.C.) for four cases. The data and example calculations are presented in the following format:

Column A: case description (one or two densifiers; with or without ferrous recovery).

Column B: hourly, daily and yearly production of d-RDF (Mg).

Column C: capital, operating and maintenance and total costs, in $/yr and $/Mg.*

Column D: revenues or savings from sale of metals and fuel, and savings from landfill avoidance and total revenues, in $/Mg.

Column E: general expression for front-end available capital, on a break-even basis. The front-end available capital is, by definition, the amount that can be afforded, in order to balance costs and revenues, for buildings, equipment, O&M and installation costs upstream of the densifier.

Column F: example expression for F.A.C. for a d-RDF sale price (k_f) of $1.42/GJ ($1.50/M Btu).

Column G: example expression for F.A.C. for a d-RDF sale price (k_f) of $2.37/GJ ($2.50/M Btu).

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*Unless otherwise indicated, $/Mg means $/Mg of d-RDF.

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TABLE 9. PART 1. FRONT-END AVAILABLE CAPITAL (F.A.C.), BREAKEVEN CASE*

A Case studied	B Production, Mg			C Densification costs				D Revenues ($/GJ)			
	/hr	/d	/yr	Capital	Operating (labor, materials, Utilities)	Maintenance	Total	Metal (a)	Fuel (b)	LF Avoidance (c)	Total
I) 1 Densifier, no ferrous recovery	3.6	50	12,500	$32,955 ($2.64/Mg)	$45,375 ($3.63/Mg)	$48,875 ($3.91/Mg)	$127,205 ($10.18/Mg)	--	174,285 k_f (13.94k_f$/Mg)	12,500 x ($x/Mg)	(b) + (c) (b) + (c)
II) 2 Densifiers, no ferrous recovery	7.2	100	25,000	$58,485 ($2.34/Mg)	$73,750 ($2.95/Mg)	$97,750 ($3.91/Mg)	$229,985 ($9.20/Mg)	--	348,590 k_f (13.94k_f$/Mg)	25,000 x ($x/Mg)	(b) + (c) (b) + (c)
III) 2 Densifiers, ferrous recovery	SEE LINE I			SEE LINE I				$22{,}500\left(\frac{1}{y}\right)$ $\frac{(\$1.80/Mg)}{y}$	SEE LINE I		(a) + (b) + (c) (a) + (b) + (c)
IV) 2 Densifiers, ferrous recovery	SEE LINE II			SEE LINE II				$45{,}000\left(\frac{1}{y}\right)$ $\frac{(\$1.80/Mg)}{y}$	SEE LINE II		(a) + (b) + (c) (a) + (b) + (c)

*Mg means Mg of RDF

k_f (sales price of fuel) in $/GJ

x (landfill cost) in $/Mg

y means yield of RDF per input ton of waste

TABLE 9. PART 2. FRONT-END AVAILABLE CAPITAL (F.A.C.), BREAKEVEN CASE*

	E General case	F Example	G Example
Case	F.A.C. ($)	F.A.C. ($), if: k_f = \$1.42/GJ, y = 0.5, α = 1.0 or (2.0) x in \$/Mg	F.A.C. ($), if: k_f = \$2.37/GJ, y = 0.5, α = 1.0 or (2.0), x in \$/Mg
I	$12{,}500 \left(\frac{13.94k_f + x - 10.18}{F_o}\right)$	\$484,875 + 50,195 x (\$345,955 + 35,815 x)	\$1,148,115 + 50,195 x (\$819,170 + 35,815 x)
II	$25{,}000 \left(\frac{13.94k_f + x - 9.20}{F_o}\right)$	\$1,066,130 + 100,390 x (\$760,675 + 71,630 x)	\$2,392,600 + 100,390 x (\$1,707,100 + 71,630 x)
III	$12{,}500 \left(\frac{13.94k_f + x + 1.8/y - 10.18}{F_\alpha}\right)$	\$665,580 + 50,195 x (\$474,885 + 35,815 x)	\$1,328,815 + 50,195 x (\$948,100 + 35,815 x)
IV	$25{,}000 \left(\frac{13.94k_f + x + 1.8/y - 9.20}{F_c}\right)$	\$1,427,530 + 100,390 x (\$1,018,530 + 71,630 x)	\$2,754,000 + 100,390 x (\$1,964,960 + 71,630 x)

* F_o = $(1 + 0.4903 + \alpha)/10$

α = 10 k_y

k_y = fraction of total front-end capital invested spent per year in O&M of front-end system (densifiers excluded)

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Thus, R.P.T. = revenue per Mg = revenue from sales of fuel/Mg + revenue from sales of ferrous/Mg* - cost of densifying/Mg + x (landfill avoidance, \$/Mg).

From this expression, the revenue per year, over an expected equipment lifetime of 10 years, is computed.

The front-end available capital is equal to

$$\text{F.A.C.} = \frac{(\text{RPT} \times \text{TPY})10}{1 + 0.4903 + \alpha} \qquad (1)$$

$$\alpha = 10\ k_y$$

in which α, k_y are the estimated fraction of the capital investment spent over a period of 10 years and one year, respectively, for operation and maintenance of the front-end equipment and facilities. For example, $k_y = 0.1$ would correspond to 10% of capital cost on a yearly basis. The term 1 + 0.4903 in the denominator corresponds to the cost of financing F.A.C. (at 8% over 10 years). TPY is the quantity of d-RDF (in Mg) sold per year.

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Equation (1) is plotted in Figures 27 and 28 versus x, the landfill avoidance cost (a variable), for the following cases:

- 1 densifier, no ferrous recovery
- 1 densifier, ferrous recovery
- 2 densifiers, no ferrous recovery
- 2 densifiers, ferrous recovery

The left-hand vertical scale corresponds to $k_y = 0.1$ ($\alpha = 1.0$), the right-hand side to $k_y = 0.2$ ($\alpha = 2$). It is believed that the latter value might be a better estimate of the percentage of front-end capital cost spent every year on that part of the plant. "y" is the yield of d-RDF per input ton of waste assumed to be 50% for these examples.

Comments

In Figures 27 and 28, it is seen that for realistic landfill costs (\$2 to \$15/Mg of waste) and the lower price of energy (\$1.42/GJ), a range of \$0.6 million to \$1.4 million (1 densifier) and \$1.3 million to \$2.9 million (2 densifiers) can be defined for the front-end available capital, if $k_y = 0.1$ (10% a year spent on maintenance and operation). This range is reduced

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*Optional

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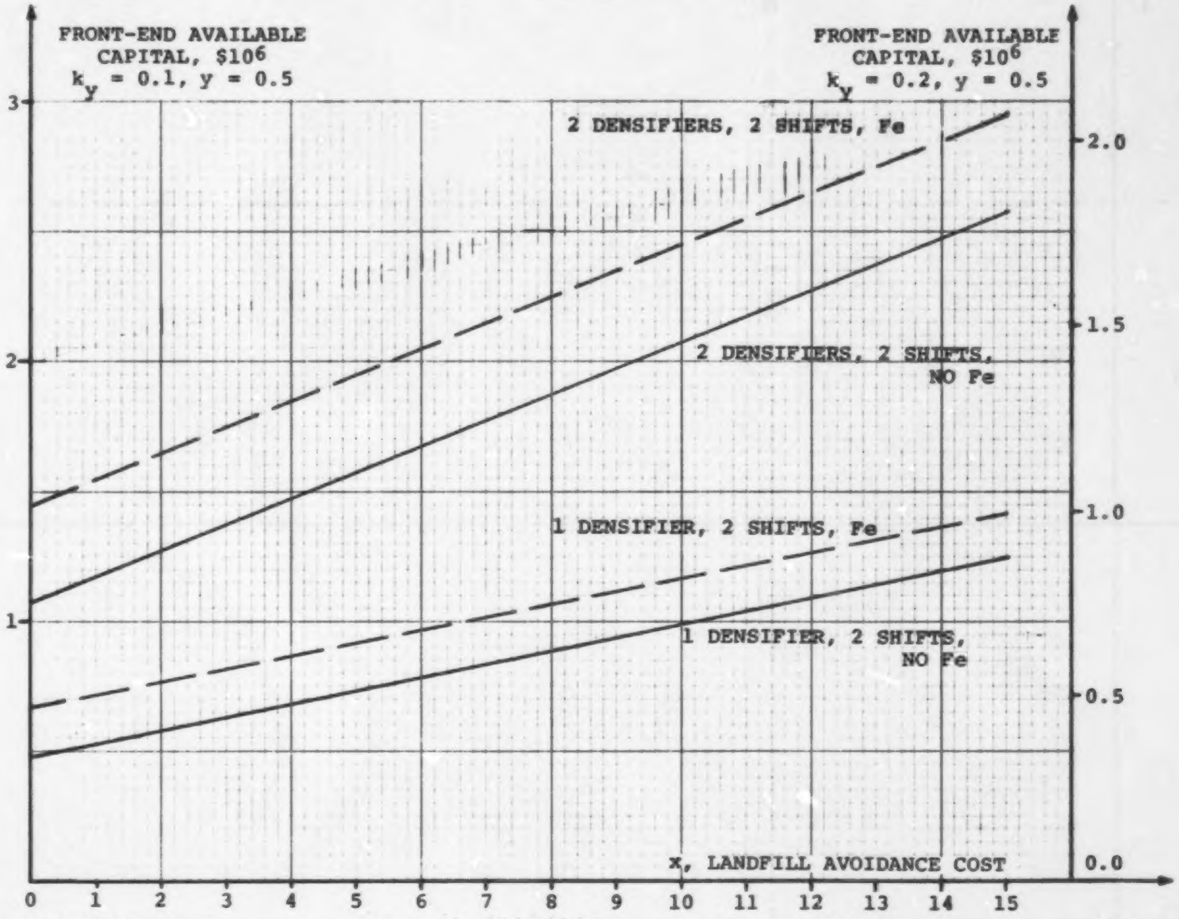

Figure 27. Sales price of energy: $1.42/GJ ($1.50/M Btu). Front-end available capital versus landfill avoidance cost.

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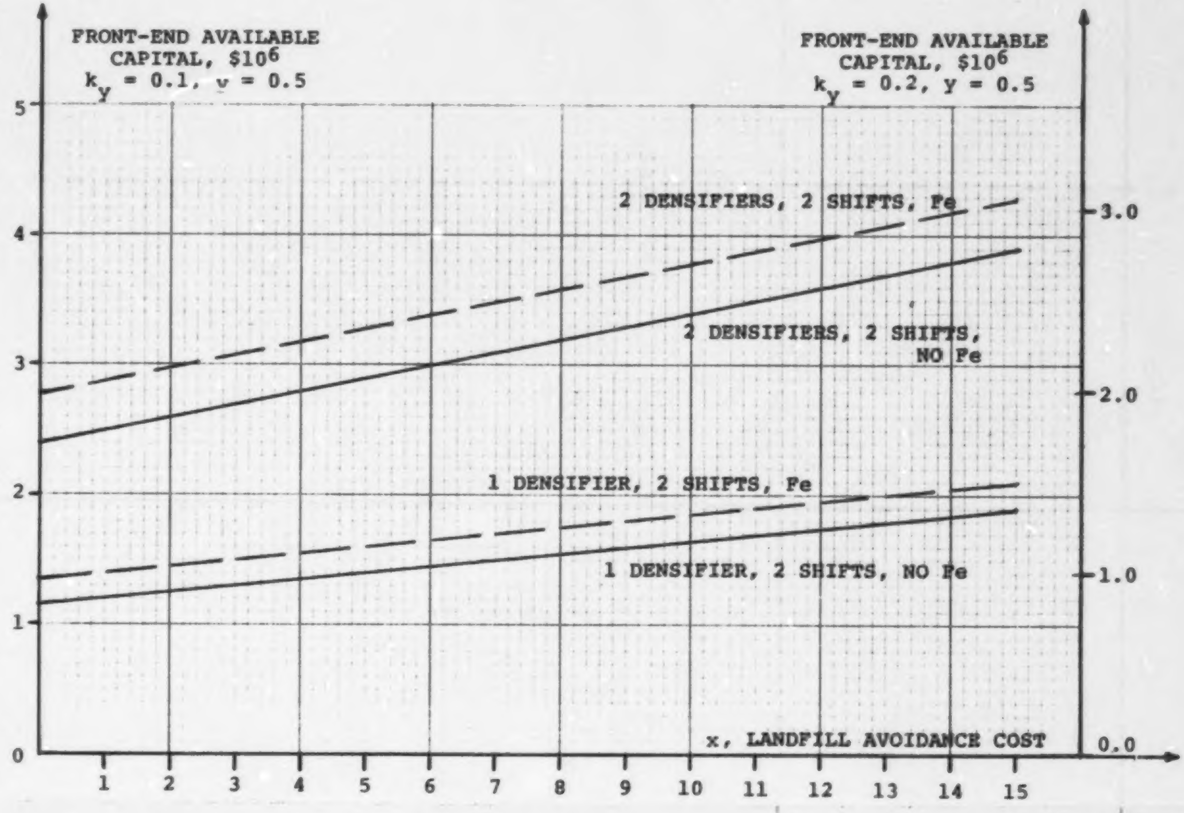

Figure 28. Sales price of energy: \$2.37/GJ (\$2.50/M Btu). Front-end available capital versus landfill avoidance cost.

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to $0.4 to $1.0 million (1 densifier) and $0.9 million to $2.1 million (2 densifiers), if k_y = 0.2 (20% a year spent on maintenance and operation).*

Size of the Facility. At the assessed d-RDF module capacity of 3.6 or 7.2 Mg/h (4 or 8 ton/h), 14 h/day, 250 day/y, the recovery plant handles 50 to 100 Mg/day (56 ton/day or 112 ton/day) of shredded RDF (fluff) feedstock to the densifier module.

It will be seen below that all alternate schemes proposed for the production of this RDF have yields "y" (in Mg RDF/Mg input waste) somewhat smaller than or equal to 50%. The size of the facility, in Mg/day of input, is 50/y or 100/y (56/y or 112/y ton/day. This is represented in Figure 29. As explained in the section entitled "Example of Plant Layout and Costing," below, a recirculation of trommel oversize can be implemented if necessary to achieve a figure of 50% for the yield of RDF (y = 0.50).

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ALTERNATE PROCESS FLOWS

General

9-1/8"

In outlining various schemes for producing, from raw municipal solid waste, an "acceptable to good" RDF feedstock, the emphasis is placed primarily on:

- simplicity of operation
- low capital and O&M costs
- production of a feedstock having a moisture level between 12% and 25%, low, inorganic fines (extrinsic ash) and free of tramp metals

Some of these requirements (such as a low ash content) might conflict with the objective of a high yield. Therefore, compromises might have to be made which relatively increase the quantity of, and thus the disposal cost of, process residuals.

---

*For the higher price of energy ($2.37/GJ), the ranges are respectively:

- if k_y = 0.1, $1.2 million to $2.0 million for 1 densifier, and $2.6 million to $4.3 million for 2 densifiers.
- if k_y = 0.2, $0.9 million to $1.4 million for 1 densifier and $1.9 million to $3.0 million for 2 densifiers.

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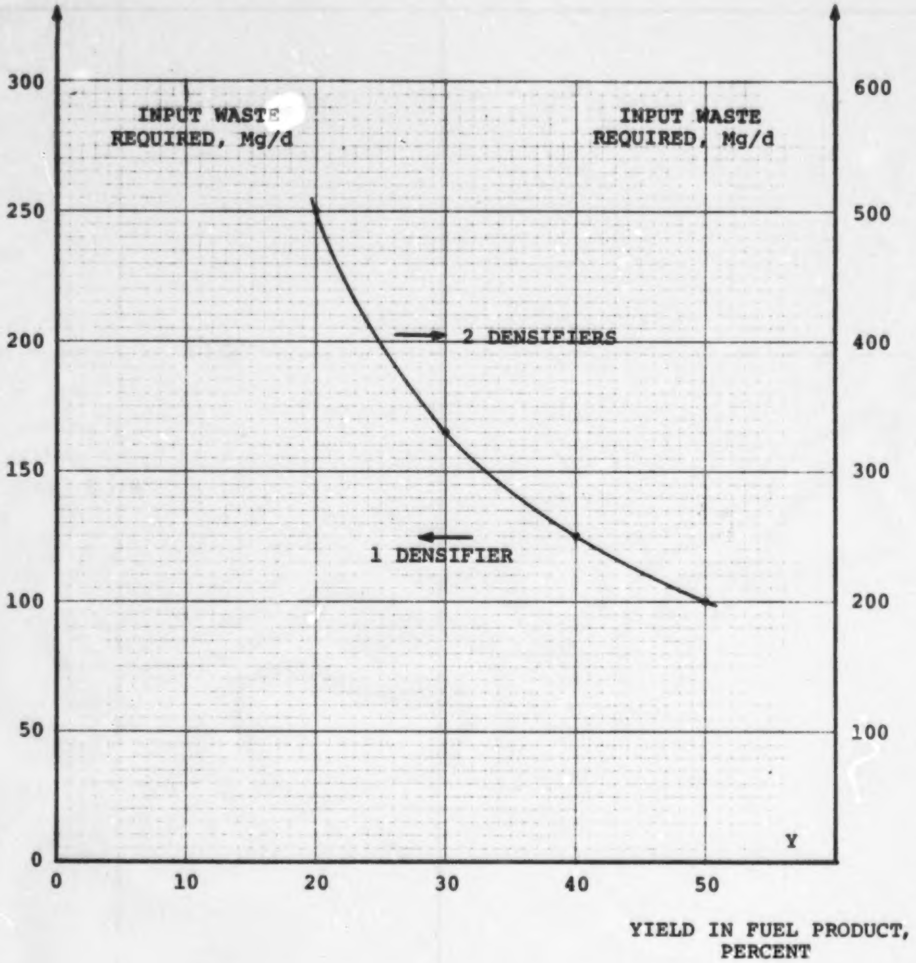

Figure 29. Required input waste versus fuel yield.

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Basic Building Blocks

Some "building blocks" which appear to be well suited to small systems are:

- the trommel (or rotary screen) which will effect the removal of glass and small organic materials with high efficiency.
- the magnetic recovery system, with a suspended drum or belt magnet. Efficiencies on the order of 85% to 90% are expected.
- the size reduction device, which only handles that fraction of the input waste to be densified as a fuel. The principal size reduction mechanism called for is a cutting action on materials such as paper, plastics and fabrics. Throughputs are only a fraction of the total input rate. Incidentally, the reliable and continuous operation of such a "knife shredder" might require the installation, immediately ahead of the shredder, of a device yet to be developed, whose function would be to remove large pieces of metal (possibly non-magnetic) present at that stage. We call it here, and on Figures 29 and 30, a "tramp metal separator."

These building blocks are the basic components of the three schemes described below.

Scheme A: Multiple Hole Trommeling

Figure 30 shows the basic process flow for Scheme A. (Tramp metals removal is sketched as an option.) Trommeling is performed on the input waste stream, unprocessed (except for the removal of white goods and oversize, bulky materials).

As an example, based on a survey of available data and results from Recovery 1, the City of New Orleans resource recovery plant, a realistic composition is given in Table 10.

Based on the New Orleans trommel evaluation (Bernheisel, et al. [24]) and other relevant data (Woodruff [25], Woodruff and Bales [26]), Table 11 presents the values relating to various components for the trommel screening efficiency, defined here as the percentage of the component present in the feedstock reporting to the undersize. The size distribution of raw waste, by component, was taken from Reference 27 as plotted by Trezek [28]. This is shown in Figure 31. Three hole sizes were selected:

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TABLE 10. ASSUMED COMPOSITION OF INPUT WASTE

Material	Wt% as-received	Component moisture as wt% as-received of total input	HHV, MJ/kg (Btu/lb), dry basis
Paper	30	5	17.43(7,500)
Cardboard	13	3	16.36(7,040)
Glass	9.2	.3	-
Garden and food wastes	25	12	17.43(7,500)
Ferrous	8	-	-
Stones	3	.9	-
Fines (<1/4")	4	.1	-
Non-ferrous	0.3	-	-
Textiles	2	.5	23.24(10,000)
Plastic	2	-	37.18(16,000)
Wood	3	1.5	20.22(8,700)
	100.0	23.3	

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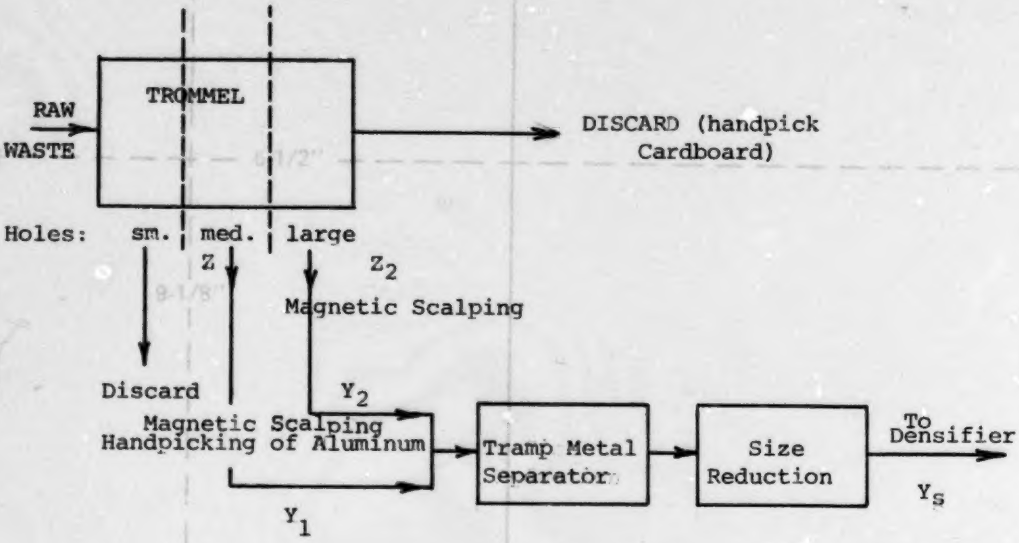
RAW WASTE
TROMMEL
DISCARD (handpick Cardboard)
Holes: sm. med. large
Z
Z_2
Magnetic Scalping
Discard
Y_2
Magnetic Scalping
Handpicking of Aluminum
Y_1
Tramp Metal Separator
Size Reduction
To Densifier
Y_S

Figure 30. Process flow - scheme A.

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TABLE 11. ESTIMATED SCREENING EFFICIENCIES OF TROMMEL

Component	η_s, Screening efficiency, %
Paper	70
Cardboard	70
Glass	99
Garden and food	90
Ferrous	85
Stones	100
Fines	98
Non-ferrous	92
Textiles	35
Plastic	78
Wood	60

Fine hole: diameter 13 mm (1/2 in.) The undersize materials, as described in Table 12, contain nearly all of the broken glass, waste, stones, nearly all of the fines and more than 50% of the food and yard wastes.

Median-size hole: diameter 102 mm (4 in.). The undersize material has a very high percentage of the non-ferrous metals, and about half of the ferrous material and sizable percentages of plastics, papers and textiles. It is probably well suited for possible hand-picking of aluminum cans (optional), and ferrous recovery. The remainder is processed into the fuel fraction. (A step of removal of remaining tramp metals, as explained above, is possible but not included in the calculations below.)

Large-size hole: diameter 254 mm (10 in.). Here the undersize has about 50% of the ferrous and relatively little garden and food wastes. Ferrous recovery is justified and is carried out. Aluminum scalping is not implemented. The remainder would contribute to

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the fuel fraction. (Again, tramp metals removal is conceivable but not included here.)

Oversize material: This fraction still contains significant percentages (of the original input weight) of paper and cardboard. Skimming of large corrugated sheets might be worthwhile. The remainder, large pieces and frames of iron, steel, aluminum and wood, is discarded.

The quantitative results of an analysis of mass balance are given in Table 12 (Parts 1 and 2). Note that at any stage in the calculation (where i = 1, 2, 3 for the first, second and third hole size, in increasing order), the third column is computed first from knowing the efficiency of screening component "k", η_k; the percentage u_{ki} of component "k" smaller than size "i", and the percentage of oversize material in the previous stage of screening, $v_{k,i-1}$ (we set $v_{k,o} = 0$). Thus, for the percentage of overs "k" at stage i, $w_{k,i}$:

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$$\text{Component k:} \quad \eta_k, v_{k,i} = 100 - w_{k,i} = \eta_k \; u_{k,i} \; \frac{v_{k,i-1}}{100}$$

Moisture losses equal to 5 points, overall, of the original total input weight, were introduced in the calculations to account for drying due to processing operations. This explains why the sum of the percentages of all fractions only amounts to 95. Based on the literature values for higher heating values of individual components listed in Table 10, the following yield and fuel specifications are obtained.

Also note that neither Table 12 nor the fuel product specification reported below reflect the optional separation of tramp, remaining ferrous or non-ferrous metals and thus would tend to understate the fuel quality.

Process A - Yield and Fuel Specification

Fuel: 13 to 102 mm (+1/2 to 4 in.) and 102 to 254 mm (+4 to 10 in.), with ferrous extracted at 90% efficiency.

Yield: $y_s = y_1 + y_2 = 15.1 + 24.2 = 39.3$ (%), as-received basis.

Moisture (compound): 22.5%, as-received basis.

Higher heating value: HHV = 13.66 MJ/kg (5,880 Btu/lb), as-received. HHV_d = 17.63 MJ/kg (7,590 Btu/lb), dry basis.

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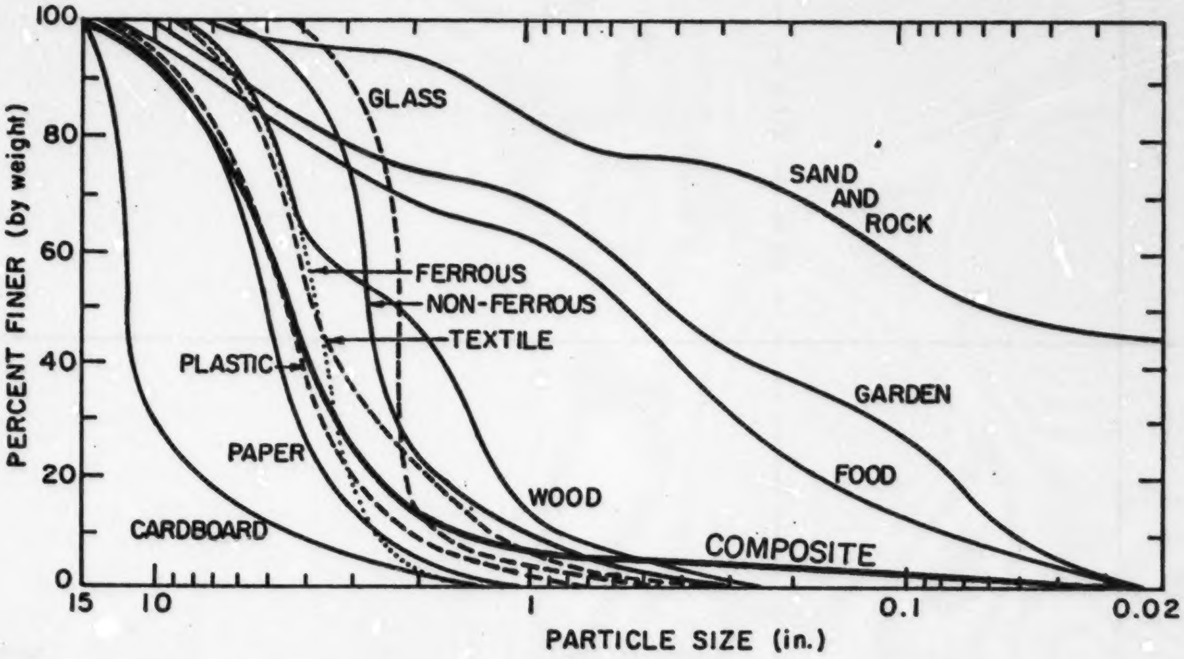

From: Ref. [28], after Ref. [27]

Figure 31. Cumulative distributions of raw waste.

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TABLE 12. PART 1. MASS BALANCE, PROCESS A, BEFORE PROCESS MOISTURE LOSSES

Constituent	% by weight of total infeed	% of fraction by weight	First holes (13 mm)				Second holes (102 mm)				Third holes (254 mm)				% by weight of total (+254 mm)	% by weight of total (-13 mm)	% by weight of total (+13 mm, -102 mm)	% by weight of total (+102 mm, -254 mm)
			EFF	% smaller than	Over	Under	EFF	% smaller than	Over	Under	EFF	% smaller than	Over	Under				
Paper	30	100	70	0	100	0	70	26	81.8	18.2	70	93	29.4	52.4	8.82	0	5.46	15.72
Cardboard	13	100	70	0	100	0	70	9	93.7	6.3	70	29	77.8	15.9	10.11	0	.82	2.07
Glass	9.2	100	99	100	1	99	99	1	0	1	99	0	0	0	0	9.11	.09	0
Garden food	25	100	90	57	48.7	51.3	90	80	22.9	25.8	90	98	4.1	18.8	1.02	12.83	6.45	4.7
Fe	8	100	85	0	100	0	85	56	52.4	47.6	85	100	7.9	44.5	0.63	0	(3.43)* 3.81	(3.2)* 3.56
Stones	3	100	100	76	24	76	100	97	3	21	100	100	0	3	0	2.28	.63	.09
Fines	4	100	98	100	2	98	98	0	0	2	98	0	0	0	0	3.92	.08	0
N.F.	.3	100	92	2	98.2	1.8	92	90	17.1	81.1	92	100	0	15.7	0	.01	.24	.05
Textiles	2.5	100	35	2	99.3	.7	35	52	81.7	17.6	35	100	53.1	28.6	1.33	.02	.44	.72
Plastic	2	100	78	0	100	0	78	38	70.4	29.6	78	95	20	50.4	.4	0	.59	1.01
Wood	3	100	60	6	96.4	3.6	60	62	61.4	35	60	100	24.6	36.8	.74	.11	1.05	1.10
Total yield (before magnetic recovery and process moisture losses), wt%															23.05	28.3	19.66	29.02

*Mass of magnetic metals removed, 90% efficiency

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TABLE 12. PART 2. MASS BALANCE, PROCESS A (PROCESS MOISTURE LOSSES CORRECTIONS)

	% by weight of total infeed		% by weight of total (-13 mm)		% by weight of total (-102 mm)		% by weight of total (-254 mm)		% by weight of total (+254 mm)		% by weight of dry fraction <		% by weight Dry f. Fe removed		ΔHHV MJ/kg dry, 102 mm unders	ΔHHV MJ/kg dry, 254 mm unders
Constituent	Dry	Water	Dry	Water	Dry	Water	Dry	Water	Dry	Water	(102 mm)	(254 mm)	102 mm unders	254 mm unders		
Paper	24	6	0	9	4.37	.73	12.58	2.10	7.06	1.18	29.83	56.04	38.95	65.36	6.79	11.39
Cardboard	10	3	0	0	.63	.19	1.59	.48	7.78	2.33	4.31	7.09	5.63	8.27	0.92	1.35
Glass	8.92	.28	8.83	.28	.09	0	0	0	0	0	.59	0	.78	0	0	0
Garden food	13	12	6.67	4.61	3.35	2.32	2.44	1.69	.53	.37	22.90	10.89	29.91	12.70	5.21	2.22
Fe	8	0	0	0	(3.43)* 3.81	0	(3.20)* 3.56	0	.63	0	26.02	15.86	3.39	1.87	0	0
Stones	2.91	.09	2.21	.07	.61	.02	.09	0	0	0	4.17	.39	5.44	.45	0	0
Fines	3.88	.12	3.80	.12	.08	0	0	0	0	0	.53	0	.70	0	0	0
N.F.	0.3	0	0	0	.24	0	.05	0	0	0	1.64	.21	2.14	.24	0	0
Textiles	2	.5	.01	0	.35	.09	.57	.14	1.06	.27	2.40	2.55	3.14	2.97	.73	.69
Plastic	2	0	0	0	.59	0	1.01	-	.40	-	4.03	4.50	5.26	5.25	1.96	1.95
Wood	1.5	1.5	.05	.05	.53	.53	.55	.55	.37	.37	3.58	2.45	4.68	2.86	.95	.58
Totals	76.5	23.5	21.58	5.15	14.65	3.88	22.44	4.97	17.83	4.51	100	100	100	100	16.55	18.19
Moisture fraction			.193		.209		0.181		.202					As-received	12.30	14.46
															(Moisture corrected)	
														As-received, compound 13.66		

*Mass of ferrous removed, 90% efficiency; Y_1 = 15.5%, Y_2 = 24.2%, Y_s = 39.3%; compound moisture: 22.2%.

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*Ash content: 10.9%, dry basis

Table 13 gives the weight distribution by component of the fuel product from Process A.

Scheme B: Flail-milling and 2-Hole Trommeling

The basic process flow is shown in Figure 32. The raw waste is flail-milled first, then trommeled. Magnetic recovery is effected on the 203 mm (8 in.) hole undersize product. Aluminum picking (by hand) is optional. The remainder of this fraction is size-reduced before densification. Again, the option of removing tramp metals prior to size reduction is sketched on Figure 32, but not included in the calculations.

Starting with the composition given in Table 10, and the size distribution in Figure 31, a size distribution for the flail-milled product is obtained and given in Figure 33. It is observed that the graphs for individual components result from a horizontal translation (towards the smaller sizes), the magnitude of which depends on the material considered. Bond's theory as applied to municipal waste [16] was used to compute the specific power (kWh/Mg) required to effect the size reduction of glass from the initial size (80% under 2.7 in.) to the desired size (80% under 0.33 in.). The power is then allotted to the other components in the proportion of their weight fraction in the mixture. The prediction is that paper will be reduced in size from -8 in. to -2.2 in., whereas the size of stones, wood and metals remain unchanged.

The mass balance is given in Table 14 (Parts 1 and 2). A five-point moisture loss is allowed for drying during processing. The following yield and fuel specifications are obtained.

Process B - Yield and Fuel Specification

Fuel: 38 to 203 mm (1.5 to - 8 in.) with ferrous extracted.

Yield: Y_s = 36.2 (%), as received basis (Figure 31).

Moisture: 21.0%, as-received basis.

Higher heating value: HHV = 13.56 MJ/kg (5,835 Btu/lb), as-received. HHV_d = 17.16 MJ/kg (7,385 Btu/lb), dry basis.

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*Based on wt percent ash (dry basis): paper = 6, cardboard = 5, food and garden = 3, textiles = 2, plastics = 2, wood = 2.

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TABLE 13. COMPONENT DISTRIBUTION IN PRODUCT FROM PROCESS A

Composition	Wt percent of size fraction (dry basis)* Less than 102 mm	Wt percent of size fraction (dry basis)* 102 mm to 254 mm	Wt percent, total fuel (dry basis)
Paper	39.0	65.4	55.2
Cardboard	5.6	8.3	7.3
Glass	.8	-	.3
Garden and food waste	29.9	12.7	19.3
Ferrous	3.4	1.9	2.5
Stones	5.4	.5	2.4
Fines (<6 mm)	.7	-	.3
Non-ferrous	2.1	.2	.9
Textiles	3.1	3.0	3.0
Plastics	5.3	5.3	5.3
Wood	4.7	2.9	3.6

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*May not add to 100% because of rounding.

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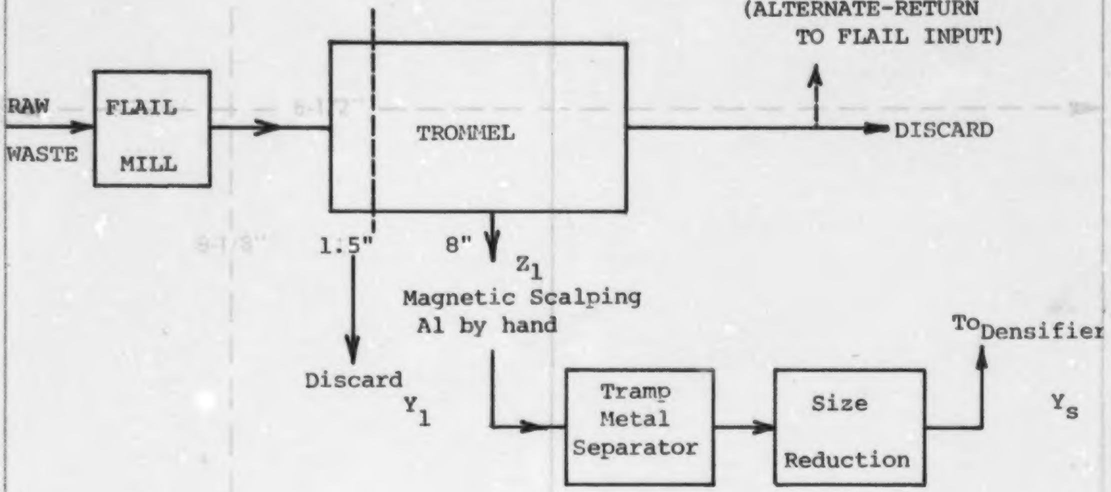
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1.5"
8"
Z_1
Magnetic Scalping
Al by hand
Discard
Y_1
To Densifier
Tramp
Metal
Separator
Size
Reduction
Y_s

Figure 32. Process flow - scheme B.

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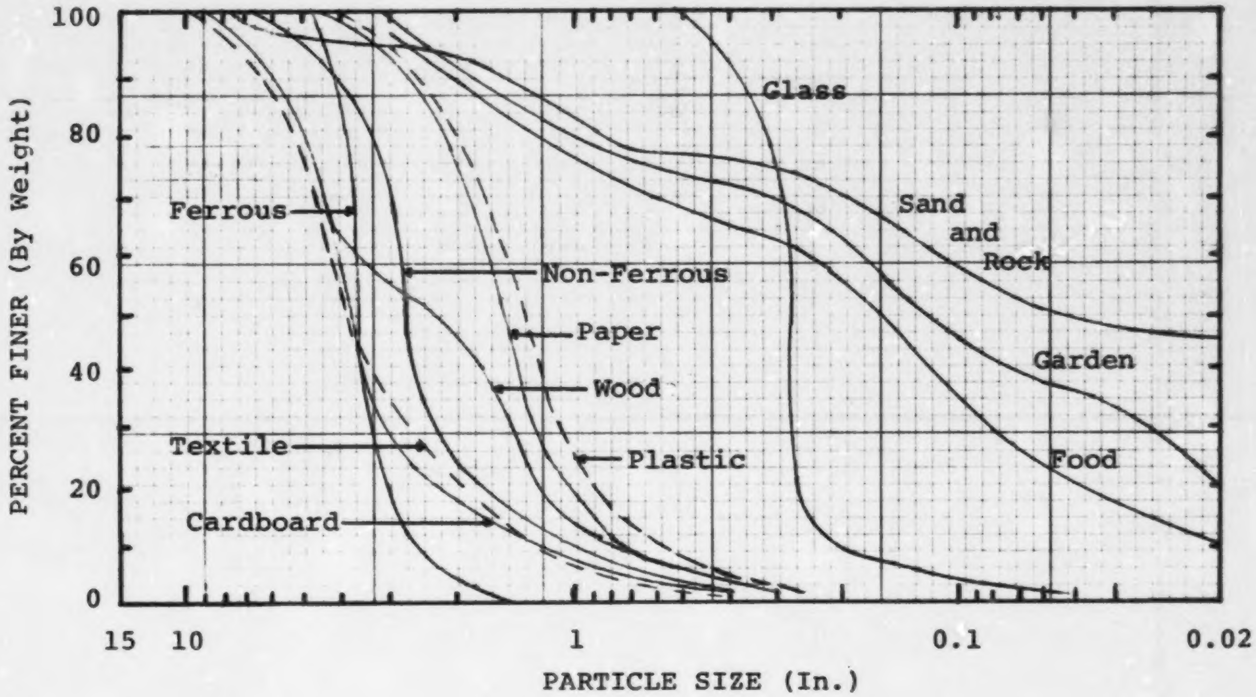

Figure 33. Computed particle-size distribution of flail-milled raw waste.

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TABLE 14. PART 1. MASS BALANCE, PROCESS B, BEFORE PROCESS MOISTURE LOSSES

Constituent	% by weight of total infeed	% of fraction by weight	First holes (38 mm)				Second holes (203 mm)				% by weight of total (+203 mm)	% by weight of total (-38 mm)	% by weight of total (+38 mm, -203 mm)
			EFF	% smaller than	Over	Under	EFF	% smaller than	Over	Under			
Paper	30	100	70	16	88.8	11.2	70	100	26.6	62.2	7.99	3.36	18.65
Cardboard	13	100	70	0	100	9	70	98	31.4	68.6	4.08	0	8.92
Glass	9.2	100	99	100	1	99	99	100	0	1	0	9.11	.09
Garden food	25	100	90	82	26.2	73.8	90	100	2.6	23.6	.66	18.45	5.9
Fe	8	100	85	12	89.8	10.2	85	98	15	74.8	1.2	.82	5.98
Stones	3	100	100	88	12	88	100	100	0	12	0	2.64	.36
Fines	4	100	98	98	2	98	98	100	0	2	0	3.92	.08
N.F.	.3	100	92	15	86.2	13.8	92	100	6.9	79.3	.02	.04	.24
Textiles	2.5	100	35	12	95.8	4.2	35	98	62.27	33.5	1.56	.11	.84
Plastic	2	100	78	52	59.4	40.6	78	100	13.08	46.4	.26	.81	.93
Wood	3	100	60	26	84.4	15.6	60	98	34.8	49.6	1.04	.47	1.49
Total yield (before magnetic recovery and process moisture losses), wt%											16.81	39.73	43.48

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TABLE 14. PART 2. MASS BALANCE, PROCESS B (PROCESS MOISTURE LOSSES CORRECTIONS)

	% by weight of total infeed		% by weight of total (-38 mm)		% by weight of total (+38 mm, -203 mm)		% by weight of total (+203 mm)		% by weight of (+38 mm, -203 mm)	% by weight (+38 mm, -203 mm) dry, Fe removed	ΔHHV MJ/kg dry (+38 mm, -203 mm)
Constituent	Dry	Water	Dry	Water	Dry	Water	Dry	Water	Dry		
Paper	24	6	2.69	.45	14.92	2.49	6.39	1.07	43.97	52.19	9.10
Cardboard	10	3	0	0	6.86	2.06	3.14	.94	20.22	23.99	3.92
Glass	8.92	.28	8.83	0.30	.09	0	0	0	.27	.31	-
Garden food	13	12	9.59	6.64	3.07	2.12	.34	.24	9.05	10.74	1.87
Fe	8	0	.82	0	(5.34)* 5.98	0	1.20	0	17.62	2.24	-
Stones	2.91	.09	2.56	.09	.35	.01	0	0	1.03	1.22	-
Fines	3.88	.12	3.80	.10	.08	0	0	0	.24	.28	-
N.F.	.3	0	.04	0	.24	0	.02	0	.71	.84	-
Textiles	2	.5	.09	.02	.67	.17	1.25	.31	1.97	2.34	.54
Plastic	2	0	.81	0	.93	0	.26	0	2.74	3.25	1.21
Wood	1.5	1.5	.23	.23	.74	.74	.52	.52	2.18	2.59	.52
Totals	76.5	23.5	29.47	7.83	33.93	7.59	13.12	3.08	100	100	17.17
Moisture fraction			.21		.18		.19		As-received, compound		13.50

Note: Y_s = 36.2%. Moisture of Fuel: 21.0%

*Mass of magnetic metals removed, 90% efficiency

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*Ash content: 9.6% (dry basis)

Table 15 gives the net percent composition of the fuel product from Process B.

TABLE 15. COMPONENT DISTRIBUTION IN PRODUCT FROM PROCESS B

Composition	Wt percent (dry basis)†
Paper	52.2
Cardboard	24.0
Glass	0.3
Garden and food waste	10.7
Ferrous	2.2
Stones	1.2
Fines (<1/4 in.)	0.3
Non-ferrous	0.8
Textiles	2.3
Plastics	3.3
Wood	2.6

Scheme C: Simplified Bureau of Mines Process

The process is directly adapted from the U.S. Bureau of Mines process [29] and is shown in Figure 34. It is assumed that the light fractions from the horizontal air classifier (cyclone 2) and from the suction hood classifiers (cyclone 1) are mixed. The heating value is taken to be the same as that quoted for the mixture of the three cyclone products in the complete process [29]. The properties of the fuel are also those given in Reference 29. Higher heating values reflect a relatively high content of plastics and rubber. Ferrous yield is 6% of the input waste.

---

*Same assumptions as for Process A.

†May not add to 100% because of rounding.

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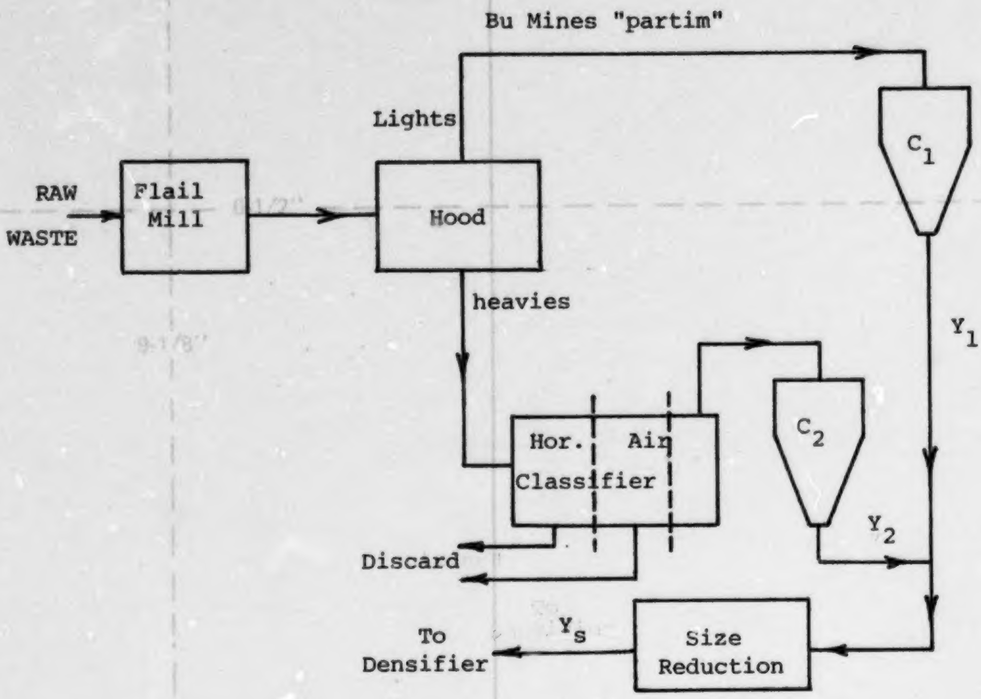
Bu Mines "partim"
Lights
RAW WASTE
Flail Mill
Hood
C_1
heavies
Y_1
Hor. Air Classifier
C_2
Y_2
Discard
To Densifier
Y_s
Size Reduction

Figure 34. Process flow - scheme C.

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Process C

Fuel: Cyclones 1 and 2 products of Bureau of Mines process.

Yield: $Y_s = Y_1 + Y_2 = 50.7\%$, as received basis.

Moisture: 8.0%, as-received basis.

Higher heating value: 18.17 MJ/kg (7,820 Btu/lb), as-received. 19.75 MJ/kg (8,500 Btu/lb), dry basis.

Ash: 7.2%, dry basis

Summary

The results summarized in Table 16 for the yield, moisture and higher heating value of fuels obtainable from Processes A, B and C show that

- a yield of about 50% is a realistic goal, provided part of all of the trommel oversize material, rich in cardboard, paper and plastics is recirculated through the flail-mill (Process B) or handpicked and size-reduced (Process A).
- a heating value of 13.94 MJ/kg, or 6,000 Btu/lb (as-received) is achievable (Process A) or definitely conservative (Processes B and C).
- moisture levels are expected to be about 20% or lower (as-received basis).
- ash contents should not exceed 11% (dry basis) or about 14% (as-received basis).

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TABLE 16. SUMMARY OF FUEL SPECIFICATIONS (PROCESSES A, B, C)

Scheme	Yield %	Moisture as-received %	Ash, dry basis %	MJ/kg (Btu/lb) as-received	MJ/kg (Btu/lb) dry basis
A	39.3	22.6	10.9	13.66 (5,880)	17.63 (7,590)
B	36.2	21.0	9.6	13.56 (5,835)	17.16 (7,385)
C	50.7	8.0	7.2	18.17 (7,820)	19.75 (8,500)

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SECTION 7

d-RDF SYSTEMS FOR SMALL COMMUNITIES: EXAMPLE FACILITY LAYOUT AND COSTING

This section describes an equipment layout and estimate costs for a front-end processing system to prepare feedstock for a densification module. The layout is based on Scheme B from the previous discussion of alternate waste-processing techniques. The costs are developed for use as the evaluation of the economic viability of a small-scale d-RDF system which follows.

The suggested d-RDF production facility layout is shown in Figure 35. Detail on equipment specification and estimates of engineering, equipment, installation and building costs (1979 basis) are presented in Appendix G. Note that for purposes of the subsequent analysis, the total front and plant cost of $1,687,700 does not include the d-RDF module costs. The cost of the d-RDF module ($389,900) has been detailed in Appendix F-1 and discussed in the earlier section of this report entitled Cost of Densification.

SYSTEM DESCRIPTION

The system illustrated in Figure 35 is sized to process, according to Scheme B (Figure 34), up to 20 Mg (22 ton/h) of municipal solid waste and produce up to 10 Mg/h (11 ton/h) of d-RDF. Actual hourly throughputs are expected to be somewhat lower (see Table 8). Waste is received and tipped on a 800 m^2 (8,600 ft^2) tipping area with a storage capacity of 200 to 250 Mg (220 to 275 tons) of material. A front-end loader pushes the waste into a shallow apron conveyor. The flail feed conveyor is inclined such that material roll-back controls the feedrate to the flail mill. The flailed product is conveyed to the trommel. Referring to Table 16, the -38 mm (-1-1/2 in.) material from the first section of the trommel contains nearly all of the glass and inorganic fines and is discarded. The intermediate -203 mm (-8 in.) fraction from the second trommel section contains the bulk of the paper and organics and passes on for further processing. The quantity of +203 mm (+8 in.) product, expected to be composed primarily of cardboard and smaller quantities of wood, textiles, plastics and paper, will be a function of the flail mill product size. Figure 35 shows this fraction conveyed to a residue container for disposal. If,

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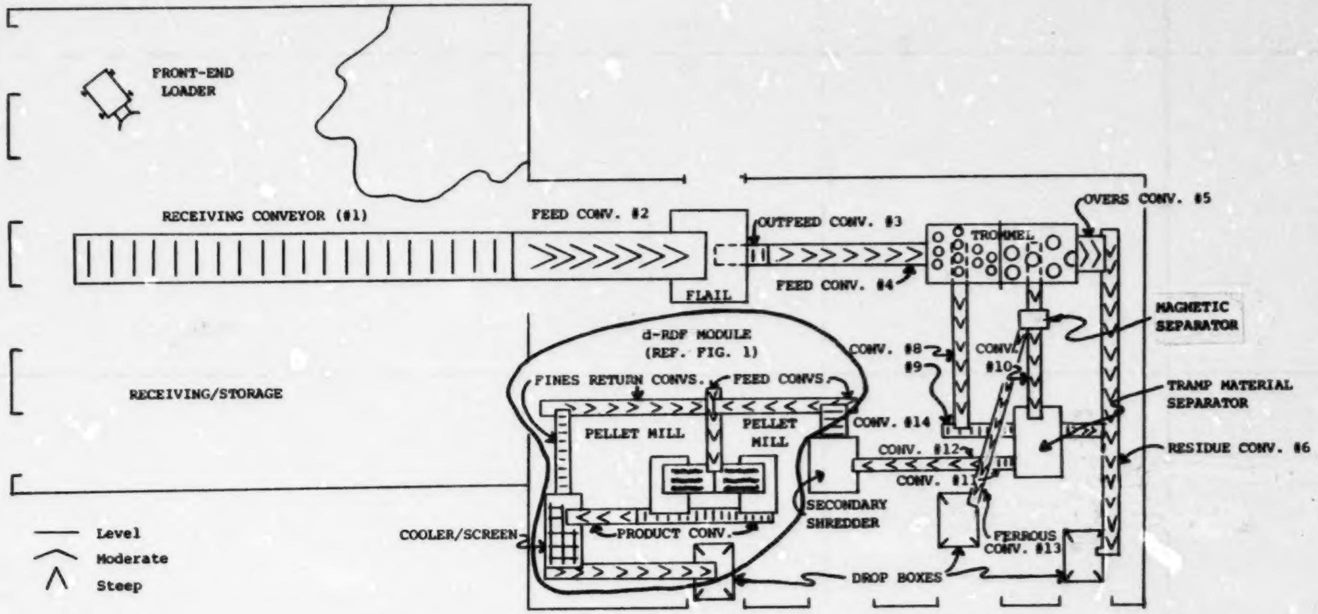
FRONT-END LOADER
RECEIVING CONVEYOR (#1)
FEED CONV. #2
OUTFEED CONV. #3
FEED CONV. #4
FLAIL
TROMMEL
OVERS CONV. #5
MAGNETIC SEPARATOR
TRAMP MATERIAL SEPARATOR
RESIDUE CONV. #6
CONV. #8
#9
CONV. #10
CONV. #14
CONV. #12
CONV. #11
FERROUS CONV. #13
SECONDARY SHREDDER
DROP BOXES
d-RDF MODULE (REF. FIG. 1)
FINES RETURN CONVS.
FEED CONVS.
PELLET MILL
PELLET MILL
PRODUCT CONV.
COOLER/SCREEN
RECEIVING/STORAGE
Level
Moderate
Steep

Figure 35. Small d-RDF production facility layout.

in fact, there is a significant level of paper and cardboard present in this fraction, minor equipment modifications would permit recouping these losses. This would involve an increase in hole size in the second trommel section or rerouting the trommel overs to the flail mill infeed. For either case, the impact on the cost estimates developed here would be negligible.

The -203 mm (-8 in.) middling fraction is conveyed to a tramp material separator. This device would most likely be a form of an air knife, and designed to remove dense materials such as non-ferrous metals, wood or large rocks and stones. The objective is to keep such materials out of the secondary shredder or densifier.

Residues from the tramp metal separator are combined with the -38 mm (-1-1/2 in.) trommel undersize fraction and conveyed past a magnet separator. The ferrous metals are separated and conveyed to one bin and the non-ferrous residue is discharged into another bin (or truck) for hauling to a landfill.

6-1/2"

Two conveyors carry the remaining organics to a secondary shredder where they are reduced to a nominal -32 mm (-1-1/4 in.) size. This product then feeds into the densifier module feed conveyors and on through a splitter into two parallel live-bottom metering bins and densifiers. The d-RDF product is screened to remove fines (which are recycled to the densifier feed) and then cooled in a pellet cooler.

9-1/8"

Not represented in the equipment layout but included in the costs are a dust control system, the operator control room, motor control center, local control stations and office facilities. The installation costs (mechanical and electrical) are estimated at 30% of the equipment cost and taxes and freight at 7%. The building costs are estimated on a unit area basis at $\$360/m^2$ ($\$34/ft^2$). Land costs are not included. Contingency and engineering costs are based on a percentage of total installed cost and are projected at 10% each.

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SECTION 8

d-RDF SYSTEMS FOR SMALL COMMUNITIES: ECONOMIC VIABILITY

In the previous section, a tentative layout and costing are developed for a d-RDF plant using two densifiers and recovering the ferrous materials.

We now refer to Figures 27 and 28 of this report for anticipated costs of

$C(D)$ = \$389,900 for the densification unit, unit, "D" (Table F-1, column 2)

$C(R)$ = \$1,687,700 for the remainder of the plant, "R"

Breakeven will occur at a combination of values of landfill cost, x^*, sale prices of energy k_f, and fraction k_y of the plant capital cost (not including the densification unit) to be spent yearly in operation and maintenance of that part of the plant. This dependence is illustrated below.

	Sale Price of Energy	
	k_f = \$1.42/GJ (\$1.50/M Btu)	k_f = \$1.90/GJ (\$2.00/M Btu)
	x^*, \$/Mg	x^*, \$/Mg
$k_y = 0.1$ (10% of C(R) for yearly O&M of "R")	2.59	(-4.02)
$k_y = 0.2$ (20% of C(R) for yearly O&M of "R")	9.34	2.74

The negative value of $x^* = -\$4.02/\text{Mg}$ ($-\$3.65/\text{ton}$) for $k_y = 0.1$ and $k_f = \$1.90/\text{GJ}$ (\$2.00/M Btu) shows that in this case, the plant should produce a net revenue, N.R. equal to

$$\text{N.R.} = 25{,}000\ (4.02 + x)\quad (\$/\text{yr})$$

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If, however, $k_Y = 0.2$, for the same sale price of energy, the plant will produce a net revenue only for landfill costs in excess of \$2.74/Mg (\$2.49/ton).

More generally, given k_Y and the corresponding line $x^*(k_F)$, for a set value $k_F = k_F^{(1)}$ of the sale price of energy, the value $x^* = x(k_F^{(1)})$ is read on the graph. The net yearly revenue is a function of the actual landfill cost, x(\$/Mg), expressed as

$$\text{N.R.} = (\text{Amount of Mg of RDF/yr}) \quad (x - x^*)$$

Figure 36, where x^* at breakeven has been plotted versus the sale price of energy, for two values of $k_Y = 0.1, 0.2$, would allow a preliminary determination of the economic viability of the proposed solution, in a particular case, for planning and analysis purposes.

Note that, since the yield in this example is 50%, the cost of disposing of the process discards is x(\$/Mg) per Mg of RDF. Therefore, the overall operation (d-RDF plant and landfill operations for the total input waste) will be self-supporting or profitable if net revenues from the d-RDF plant balance or exceed the cost of disposal of the remainder, or since $x \geq 0$, if

9-1/8"

$$x^* \leq 0 \text{ or } k_F \geq k_F \ (x^* = 0)$$

This is realized for all values of (x, k_F) in the quadrant defined by the horizontal axis and the vertical axis drawn through the intercept of line $k_F = k_F \ (x^* = 0)$ with the horizontal axis, for the assumed value of k_Y.

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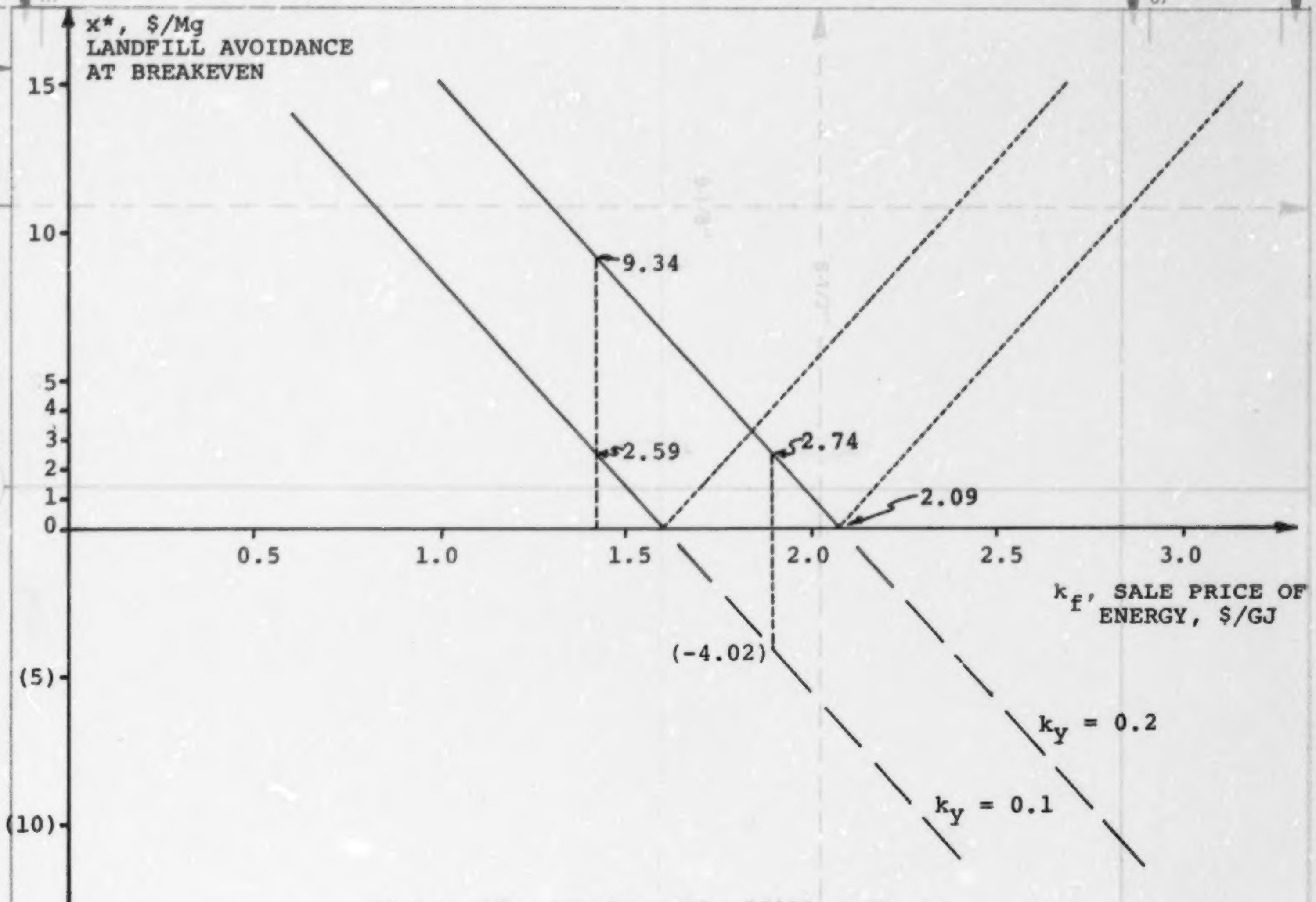

Figure 36. Breakeven landfill cost sale price of energy for $k_y = 0.1$, $k_y = 0.2$

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APPENDIX A. SUMMARY OF SOLID WASTE AND BIOMASS DENSIFICATION AND d-RDF TEST BURNS

Prepared by: NATIONAL CENTER FOR RESOURCE RECOVERY

December 1979

TABLE A-1. SOLID WASTE & BIOMASS DENSIFICATION SUMMARY

Operator/Owner	Location	Operating Period	Plant Type	Feed-stock	Reported Capacity	Front end	Densi-fier	Desc.	End Uses	Comments
Agnew Environmental Products	Grants Pass, OR	1978-pres.	Pilot plant	wood waste	500-1000 lbs/hr	Dryer	Hausmann briquetter	1-3" ø	Industrial boilers	Have tested air classified waste as well
(clients)	Nebraska Wisconsin	N.A.	Comm.	Wood waste	500-1000 lbs/hr (densifiers available up to 6600 lbs/hr)	Dryer	Hausmann briquetter	2-3½" ø	Industrial boilers	Clients using briquetter on full time basis No binders used
Bio-Solar R & D Corp. (Woodex)										
Main Plant	Brownsville, OR	1972-pres.	Comm.	Typically wood wastes, hog fuel, slash, bark, sawdust	150 TPD to 900 TPD; 300 TPD typical	(Typical) hog 2" sand sep hog 1/8", dry to 18-22% M.C., extrude to controlled 9-12% M.C.	Calif. Pellet Mill	1/4" ø x 1/2" to 1 1/2" length	Stoker boiler, suspension (regrind), other	32-34 PCF. 8500 Btu/lb, 1-3% ash, investigated 42 biomass feedstocks. Bagasse & rice straw in Lake Harbor, FL
Hines Lumber	Hines, OR	Var. 1977-1979								
Sierra Power	Fresno, CA									
Western Power	Redding, CA									
Pullman/Woodex	Greensville, NC									
Tennesee/Woodex	Knoxville, TN									
Western Engrg.	British Columbia	Startup or Construc.								
Woodex, MI	Menominee, MI									
Day Resources	Stand Point, ID									
Woodex	Lake Harbor, FL									
Woodex	Pulaski, WI									

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TABLE A-1 (Continued).

Operator/Owner	Location	Operating Period	Plant Type	Feed-stock	Reported Capacity	Front end	Densi-fier	Desc.	End Uses	Comments
California Pellet Mill Co. (CPM)	Crawfordsville, ID	Equipment manufacturer	Pilot plant	Agricultural feeds & wastes; wood wastes, solid wastes	Variety of machine sizes, 2 to 15 TPH	Generally not provided	Ring extrusion type	Varies, 1/8 to 1 1/4" ø	Feed, fuels	Supplied densifier to Woodex, Guaranty Fuels, Lehigh Forming Co., NCRR and Vista
Dakota Pelleting Corp.	Watertown, SD	1976-pres.	Comm.	Flax processing waste	7-8 TPH	Several shredding & grinding operations	Calif. Pellet Mill	1/4" ø x 1/2-1" length	Heat recovery incinerator, underfeed stokers, overfeed travelling grate stokers, overfeed dump grate stokers	Stockpiles of pellets available for purchase $40/ton. Schools, businesses and industries using pellets. Some burn 100% pellets
National Center for Resource Recovery, Inc.	Equipment Test and Evaluation Facility Washington, DC	1974-1979	Pilot plant	MSW, office waste	2 1/2-3 TPH	Shred, screen, air classify, secondary shred	Calif. Pellet Mill	1/2" ø, 5/8-3/4" long	Test burns at Hagerstown, MD; Erie, PA; Pentagon, DC	1500 tons produced; operations discontinued June 1979

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TABLE A-1 (Continued).

Operator/Owner	Location	Operating Period	Plant Type	Feed-stock	Reported Capacity	Front end	Densi-fier	Desc.	End Uses	Comments
Ferro-Tech (client)	Connecticut	Start Fall 1979	Comm.	Sawdust	9 TPD	1/16" feedstock	Ferro-Tech roll briquetter	2 cc 3/4" x 1/2"	Stoker boiler	6-8 pcf feedstock, 25-30 pcf product, 5% M.C., no binders
Frajon, Inc.	Frona, MO	Started 1979	Comm.	Wood waste	N.A.	N.A.	N.A.	N.A.	N.A.	Use of binders
Guaranty Fuels/ Stillwater Associates	State Prison Stillwater, MN	3/79-pres.	Comm.	Wood chips	150 TPD	Dryer, dust collector, hammer mill, pelletizer, cooler-screen	Calif. Pellet Mill	3/8" Ø x 1" long	Travelling grate stoker	First plant - presently inconsistent supply wood-chips
Lehigh Forming Co.	Easton, PA	1977-pres.	Pilot plant	MSW, coal fines, wood & paper wastes	10 TPH	Magnetic separation, air classify, shred	Calif. Pellet Mill	5/8" Ø x 1 1/4" long	Stoker boilers tests	Production for market development testing

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TABLE A-1 (Continued).

Operator/Owner	Location	Operating Period	Plant Type	Feed-stock	Reported Capacity	Front end	Densi-fier	Desc.	End Uses	Comments
National Recycling Corp.	Fort Wayne, IN	1971-1973	Proto-type	MSW	5-15 TPH	Shred, air classify, screen	Modified John Deere cubetter	Cubes, 1 1/2" x 1 1/2" x 1-3"	Ft. Wayne municipal power plant - test firing	No longer in business
Papakube Corp.	San Diego, CA	1976-pres.	Pilot plant test facility	MSW, wood waste	8-10 TPH	Not provided	Papakube cubetter	1 1/4" x 1 1/4" x 1-3"	Stoker boilers	Equipment supplier based on John Deere technology, production for market develop-ment testing
Sprout-Waldron	Muncy, PA	Present	Pilot plant	Agri-cultural feeds & wastes wood, solid waste	Variety of machine sizes, 2-15 TPH	Not provided	Ring extru-sion type	Varies 1/8" x 7/8" Ø	Feeds, fuels	Supplier for Teledyne
U.S. Navy	Jacksonville, FL, Naval Air Station	In constr.	Experi-mental facility	Base waste (MSW, comm.)	40 TPD maximum	Flail, trommel, classify	Sprout Waldron	3/4" Ø	Evaluate in stokers	2-3 year research program to begin in mid-1980

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TABLE A-1 (Continued)

Operator/Owner	Location	Operating Period	Plant Type	Feed-stock	Reported Capacity	Front end	Densi-fier	Desc.	End Uses	Comments
Teledyne National	Cockeysville, MD	1976-pres.	Comm.	MSW	7 TPH (2 densifiers)	Shred, magnetic separation, air classify, trommel, screen, secondary shred	Calif. Pellet Mill & Sprout Waldron	1" & 1/2" ø	Stoker boilers	Production for Erie & market development testing. Currently involved in 3 year contract to provide 20,000 tons to Wright-Patterson AFB, OH
Vista Chemical & Fiber Products	Los Gatos, CA	1974-pres.	Prototype	MSW, paper waste	5-8 TPH	Pre-trommel, magnetic separation, air classify	Calif. Pellet Mill	1/4" to 1 1/2" ø, length varies	Stoker boilers	Production for market development testing

Comm. - Commercial plant
R & D - Research & Development
M.C. - Moisture content (dry wt.)

TPD - Tons per day
N.A.- Information not available

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Prepared by: NATIONAL CENTER FOR
RESOURCE RECOVERY
April 1979

TABLE A-2. d-RDF TEST BURN SUMMARY

LOCATION	USER	SPONSOR	DATE	BOILER DESCRIPTION	MATERIAL QUANTITY AND DESCRIPTION	PRODUCER	COMMENTS
Ft. Wayne, IN	Ft. Wayne Mun. Power Co.	Ft. Wayne	1972	Underfeed-multiple retort	40 T 1¼" x 1¼" x 2" cubets	National Recycling Corp.	3:1 by vol. (?) 6850-8530 Btu/lb Roy F. Weston
Eugene, OR	Eugene Water & Electric Board	Eugene W&E	10/74	155 M lb/hr traveling chain grate-spreader stoker	21 T 3/8" pellets 105 T fluff (from St. Louis	Vista	Sandwell International five 6 to 7 hour tests
Appleton, WI	Consolidated Paper	Wisconsin Solid Waste Recycling Authority	5/76, 10/76	52 M lb/hr modified for gas; tested with gravity feed, manual ash removal	40 T 3/4" pellets	Grumman	Market development test
Waupun, WI	Waupun State Prison	Wisconsin Solid Waste Recycling Authority	6/76	35 M lb/hr spreader stoker-vibragrate	20 T 3/4" pellets	Grumman	20-30-40% pellets by heating value Market development test
Oshkosh, WI	U. of Wisconsin	Wisconsin Solid Waste Recycling Authority	8/76	45 M lb/hr spreader stoker-vibragrate gas or coal	20 T 1-1/8" pellets 27 PCF density	Vista	1:1 & 1:2 blends Market development test
Green Bay, WI	Ft. Howard Paper	Wisconsin Solid Waste Recycling Authority	11/76	275 M lb/hr B&W spreader stoker	40 T 3/4" pellets	Grumman	1:3 & 1:2 blends Market development test
Menasha, WI	Menasha Paper Board	Wisconsin Solid Waste Recycling Authority	10/76	165 M lb/hr spreader stoker	20 T 3/4" pellets	Grumman	3:2 blend Market development test
Palmerstown, PA	Hercules Cement	Unknown	4/75	Cement kiln	Reground 200 T - 1 1/8" & 5/8" pellets	Vista	7 day test - problems in regrind with existing pulverizers
Sunbury, PA	Pennsylvania Power & Light	Unknown	5/75	Suspension fired utility boiler	Reground 80 T 5/8" pellets	Heikki Elo	2 day test
Piqua, OH	Piqua Mun. Power Plant	Unknown	6/75	150 M lb/hr C.E. chain grate, gravity overfeed	22 T 3/8" pellets	Black Clawson	1:1 vol.; 6400 Btu/lb Franklin pulp product dried and pelletized

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TABLE A-2 (Continued).

LOCATION	USER	SPONSOR	DATE	BOILER DESCRIPTION	MATERIAL QUANTITY AND DESCRIPTION	PRODUCER	COMMENTS
Dayton, OH	Wright-Patterson A.F.B.	Air Force	7/75	80 M lb/hr traveling grate - Detroit spreader stoker	40 (?) T 3/8" pellets	Black Clawson	34 hr 1:1; 6 hr 1:2 Product as above
Champagne, IL	Chanute A.F.B.	Air Force	9-10/75	35 M lb/hr traveling chain grate - gravity overfeed	150 T 1 1/8" pellets	Vista	1:1 & 0:1; 4 box cars Material degraded in transit and long storage
Hagerstown, MD	Maryland Correctional Institute (MCI)	EPA	3,5/77	60 M lb/hr Erie City spreader stoker	280 T ½" pellets	NCRR	58 hr 1:1, 53 hr 1:2 29 hr 0:1
Hagerstown, MD	M.C.I.	Maryland Environmental Services (MES)	Fall/78	As above	250 T ½" & 1" pellets	Teledyne	3 test burns over couple months
Spring Grove, PA	P. H. Glatfelter Co.	M.E.S.	Fall/78	Small bark boiler	100 T ½" & 1" pellets and some fluff	Teledyne	Market development test
Maryland - 5 Locations	Institutional Boilers	M.E.S.	1977-78-79	Five 10 M lb/hr boilers	<20 T ½" & 1" pellets each test	Teledyne	Market development test
Not revealed	Not revealed	Private	1977	50 M lb/hr underfeed stoker	<25 T 3/8" & 5/8" pellets	Heikka Elo	Up to 100% pellets Market development test
Not revealed	Not revealed	Private	1978	150 M lb/hr overfeed stoker	<25 T 5/8" plant waste pellets	Heikki Elo	Market development test
Vestal, NY	Harper College	Raytheon/State of NY	11/70	100 M lb/hr vibragrate - mass feed stoker	25 T 1" pellets	NCRR	0:1 & 1:1 blend; burnback; degraded pellets-jams Market development test
Washington, DC	GSA-Virginia Heating Plant	DOE/GSA	3/79	70 M lb/hr underfed multiple retort	125 T ½" pellets - office wastes	NCRR	30 hr 4:1; 30 hr 2:3 90 hr 3:2; 6600 Btu/lb

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LOCATION	USER	SPONSOR	DATE	BOILER DESCRIPTION	MATERIAL QUANTITY AND DESCRIPTION	PRODUCER	COMMENTS
Erie, PA	General Electric	EPA	3-4/79	125 M lb/hr spreader stoker	2000 T ½" pellets	NCRR 700 T Teledyne 1300 T	
Dayton, OH	Wright-Patterson A.F.B.	Air Force	5/79-5/80	80 M lb/hr spreader stoker - traveling grate	±4000 T ½" pellets	Teledyne	Contract for $27/ton F.O.B. plant

Criteria/Notes: Catalog tests >10 tons pellets from wastes ratios expressed as coal:pellets

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APPENDIX B

PUBLICATIONS RESULTING FROM THE WORK UNDER EPA GRANT NO. 804150

Alter, Harvey, and J. M. Arnold. Preparation of Densified Refuse-Derived Fuel on a Pilot Scale. Proceedings, Sixth Mineral Waste Utilization Symposium, U.S. Bureau of Mines and IIT Research Institute, Chicago, Illinois. 1978. pp. 171-177.

Alter, Harvey, and J. A. Campbell. The Preparation and Properties of Densified Refuse-Derived Fuel. Paper presented at American Chemical Society Symposium on Thermal Conversion of Solid Wastes and Biomass, Washington, D.C. 1979. 15 pp.

Arnold, J. M., and D. C. Hendrix. Initial Mass Balance for Production of Densified Refuse-Derived Fuel. Technical Report RR77-3, National Center for Resource Recovery, Washington, D.C. 1977. 6 pp.

Campbell, J. A., and R. Reinoldi. Properties of Densified Refuse-Derived Fuel. Technical Investigation 79-9, National Center for Resource Recovery, Washington, D.C. 1980. (in press).

Natof, S., and J. M. Arnold. The Preparation of Densified Refuse-Derived Fuel: Initial Operating Report. Technical Report 77-1, National Center for Resource Recovery, Washington, D.C. 1977. 13 pp.

Wiles, C. W. The Production and Use of Densified Refuse-Derived Fuel. Paper presented at Fifth Annual Research Symposium, Land Disposal and Resource Recovery, U.S. Environmental Protection Agency, Office of Research and Development, Orlando, Florida. 1979. (Proceedings in press).

Wiles, C. W. Densified Refuse-Derived Fuels - An Alternative Concept. Proceedings, Conference on Status and Research Needs in Energy Recovery, U.S. Environmental Protection Agency, Municipal Environmental Research Laboratory, Hueston Woods, Ohio. 1976.

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APPENDIX C

PROCEDURES FOR MEASURING PELLET MILL ROLLER AND DIE WEAR

METHOD C.1

Roller Wear Measurement Procedure

1.0 Diameter Measurement Procedure

1.1 Place roller on flat, hard surface with axis of rotation parallel to this surface. The face of roller with identifying markings is termed outside face (which is also the end facing the feed screw) and the other face is termed the inside face.

1.2 Select a flat bar 6-12 mm thick, 25 mm wide and 250 mm long and checked to be flat and true. Place the narrow edge of the bar directly on top of the roller, parallel to the roller axis. If roller surface is convex, use bubble level to assure the bar and roller axis are parallel.

1.3 Use a meter stick graduated in mm to measure the perpendicular distance from the resting surface to the bottom of the flat bar at both the inside and outside edges of the roll. Record these measurements as: outside face diameter and inside face diameter. If surface is convex, record as convex diameter.

1.4 Remove the bar and replace it again as outlined in step (2). This preserves the independence of the next measurements.

1.5 Repeat steps 2, 3, and 4 until 20 measurements are attained.

1.6 Turn the roller 90° and repeat steps 2 through 5.

2.0 Circumference Measurement Procedure

2.1 Wrap a tape measure graduated in mm around the inside and outside edge of the roller surface. Record these measurements.

2.2 Remove tape and repeat step 1 until 20 measurements are recorded.

2.3 Wrap the tape measure around the center of the roller surface (approximately 8 cm from edge). Record this circumference measurement.

2.4 Remove tape and repeat step 3 until 20 measurements are recorded.

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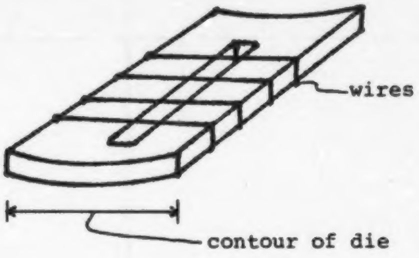
METHOD C.2

Die Wear Measurement Procedure

1.0 Test Apparatus

1.1 Depth Gauge Mounting Jig - consists of 22.5 cm long x 83 mm wide x 6 mm thick steel plate with a 8 mm wide and 125 mm long slot centered in its middle. The width side is curved to fit the contour of the die. Four wires (14 gauge) 25 mm apart and beginning 75 mm from either end, run perpendicular to the length. Each wire connects a pair of V-slots etched in the edge to prohibit the wires from slipping.



1.2 Large C-clamp (25 cm opening) and wood block 12 cm x 12 cm x 38 mm.

1.3 Two Jig Maintaining Rods - for 13 mm die, 12.5 mm diameter x 12 cm long; for 25 mm die, 24 mm diameter x 12 cm long.

1.4 Depth Gauge - accurate to .001".

2.0 Test Preparation

2.1 Select four columns of die holes (parallel to the die's axis of rotation) 90° apart around the inside circumference of the die. Mark them #1, 2, 3, and 4.

2.2 Remove the pad and clean the die surface (with wire brush) of an area covering 4 columns of holes centered around columns 1 to 4. Also, clear all the holes in this area to a depth of 1/2".

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2.3 Along column #1, insert the jig position maintaining rod in each of the holes at either end of the column.

2.4 Place the jig into the die, snuggly against the right side of the two rods and centered over the die face at an equal distance from the outside and inside of the die. Secure with wood block and C-clamp.

3.0 Test Procedure

3.1 Insert the depth gauge into the jig slot snug to the outside wire ("outside" = toward the feed end of the pellet mill). Designate this location #1A. The depth gauge skirt must bear against the side of the wire and the depth gauge probe able to touch the die's surface (rather than probing a hole). If it probes a hole, move it to the opposite side of the wire.

3.2 Record the position of the depth gauge at position #1A, i.e., whether in front of or behind the wire; on the right or left side of the slot.

3.3 Once an exact position is noted, lower the gauge probe until it touches the die surface. (Let the ratchet click once). Record the gauge reading to the nearest ten thousandth of an inch, remove the gauge and replace it in the exact spot.

3.4 Repeat step 2 until 20 readings are recorded.

3.5 Repeat steps 1 through 3 for each of the next three wire positions to be designated 1B, 1C, and 1D.

3.6 Repeat the test preparation and procedures for columns of holes 2, 3, and 4.

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APPENDIX D

METHODS FOR TESTING d-RDF SAMPLES

METHOD D.1

d-RDF Moisture Content Determination

1.0 Apparatus

1.1 Drying pans - 45 cm x 45 cm x 4 cm. Stable at temperatures to 200°C.

8-1/2"

1.2 Drying oven - Freas Model 845 - 0-200°C range. Interior dimensions 48 cm D x 94 cm W x 63 cm H. Forced-draft to remove moisture-laden air.

9-1/8"

1.3 Balance - precision, 0.1 g.

2.0 Laboratory Sample Collection

2.1 Collect 4-7 kg of d-RDF from the discharge of the pellet mill in a tared polyethylene bag. Immediately seal the bag air-tight.

2.2 Label sample as to sample number, date, time, contents, and collection point.

3.0 Test Procedure

3.1 Weigh bag with sample and record weight. Subtract tare weight from gross to obtain as-received d-RDF sample weight.

3.2 Empty content of bag onto clean, tared drying pan, spreading evenly across pan so burden height does not exceed 5 cm. If height exceeds 5 cm, sample is split between two or more pans.

3.3 Place pans with sample in oven at approximately 105°C. Remove after 24 hours. Record weight of dry d-RDF sample.

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4.0 Calculations

4.1 Percent moisture, dry weight basis = $\frac{A - B}{B} \times 100$

4.2 Percent moisture, as-received basis = $\frac{A - B}{B} \times 100$
where:

A = weight of as-received sample
B = weight of dry sample

METHOD D.2

d-RDF Ash Content Determination

1.0 Apparatus

1.1 Crucibles - 50 ml glazed porcelain.

6-1/2"

1.2 Furnace - Thermolyne Type 1500 muffle furnace 0-1200°C range. Interior dimensions 10 cm W x 9 cm H x 23 cm D

1.3 Balance - Mettler Analytical, precision, 0.05 mg.

9-1/8"

1.4 Riffle Sampler - 18 chutes of 2.5 cm width.

1.5 Desiccator.

2.0 Laboratory Sample Collection

2.1 Riffle oven-dried d-RDF (see Moisture Content Determination - Method D.1) to obtain 20-25 gram sample.

2.2 Repeat 2.1 for a total of two samples.

3.0 Test Procedure

3.1 Tare two clean and fired (at 600°C for one hour) crucibles. Place a riffled d-RDF sample in each. Weigh and record weights of the two loaded crucibles to 0.1 mg.

3.2 Place both samples in muffle furnace at 600°C for six hours.

3.3 Remove crucibles, place in desiccator and cool to ambient temperature. Weigh and record weight of each crucible. Replace in furnace at 600°C for two hours.

3.4 Repeat step 3.3 until constant weight is reached.

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3.5 Calculate percent ash for each sample. If difference in results is greater than 1.5%, repeat 3.0.

4.0 Calculations

4.1 Percent ash, dry weight basis =

$$\frac{(B_1 - T_1) + (B_2 - T_2)}{(A_1 - T_1) + (A_2 - T_2)} \times 100$$

A = weight of sample plus crucible before ignition
B = weight of sample plus crucible after ignition
T = crucible tare weight

METHOD D.3

d-RDF Bulk Density Determination

6-1/2"

1.0 Apparatus

1.1 Bulk density sample box - wooden, 30.5 cm x 30.5 cm x 30.5 cm interior. Box is tared.

9-1/8"

1.2 Scale - Platform type; precision, 0.1 lb.

2.0 Sample Collection

2.1 At the discharge point of pellet mill, collect a one cubic foot sample of d-RDF, making sure to collect sample from entire belt width.

3.0 Test Procedure

3.1 Carefully level the overflow. Weigh and record weight of box with d-RDF. Empty box.

3.2 Repeat steps 2.1 and 3.1 for a total of three determinations.

4.0 Calculations

4.1 Bulk density (lbs/ft³) = $\frac{(W_1 - T) + (W_2 - T) + (W_3 - T)}{3}$
where:

W = weight of d-RDF and box
T = box tare weight

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METHOD D.4

d-RDF Pellet Density Determination

1.0 Apparatus

1.1 Vernier Calipers - range 0 to 120 mm in 0.1 mm divisions.

1.2 Analytical Balance - precision, 0.1 mg.

1.3 Riffle Sampler - 18 chutes of 2.5 cm width.

2.0 Laboratory Sample Collection

2.1 Collect 4-7 kg of d-RDF from the discharge point of the pellet mill in a polyethylene bag.

2.2 Riffle sample to obtain 10 to 20 pellets. Discard pellets less than 0.5 cm in length.

3.0 Test Procedure

3.1 Measure and record diameter of each pellet twice.

3.2 Measure and record the length of each pellet twice. In measuring, keep the jaws of the calipers at right angles with a discernible side of the pellet. Measure a length most nearly representative of an average length.

3.3 Weigh and record the sum weight (M_s) of the measured pellets.

4.0 Calculations

4.1 Calculate the average diameter of each pellet (D_i).

4.2 Calculate the average length of each pellet (L_i).

4.3 Calculate the volume of each pellet (V_i).

$$V_i = \frac{\Pi \times (D_i)^2 \times L_i}{4}$$

4.4 Calculate the sum pellet volume (V_s)

$$V_s = \sum_{i=1}^{n} V_i$$

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4.5 Calculate pellet density

$$\text{Pellet Density (g/cm}^3\text{)} = \frac{M_s}{V_s}$$

METHOD D.5

d-RDF Fines Content (-3/8 inch) Determination

1.0 Apparatus

1.1 Screener - Rotex Model #12 GP, equipped with 91 cm x 50 cm square-holed sieve having 9.5 mm (3/8 inch) actual openings.

1.2 Balance - precision, 0.1 g.

2.0 Sample Collection

2.1 From the discharge point of the pellet conveyor from the pellet mill, collect a 4-7 kg sample of d-RDF in a polyethylene bag. Make sure to sample entire width of belt. Immediately seal the bag air-tight.

2.2 Label sample as to sample number, date, time, contents and collection point.

3.0 Test Procedure

3.1 Weigh and record bagged sample weight.

3.2 Empty d-RDF sample onto screener. Spread sample over screen so that burden height does not exceed one inch. Reseal bag with remainder of sample.

3.3 Weigh and record bag tare weight.

3.4 Run machine for three minutes.

3.5 Weigh and record weight of screen unders.

3.6 Repeat 3.2 - 3.5 until entire sample is screened.

4.0 Calculations

4.1 Calculate percent fines content.

$$\text{Percent fines} = \frac{B}{(A - T)} \times 100$$

where:

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B = total screen unders weight
A = bagged sample weight
T = bag tare weight.

METHOD D.6

d-RDF Mean Length Determination

1.0 Apparatus

1.1 Riffle Sampler - 18 chutes of 2.5 cm width.

1.2 Vernier Calipers - range 0 to 120 mm in 0.1 mm divisions.

2.0 Laboratory Sample Collection

2.1 From discharge point of the pellet conveyor from the pellet mill, collect a 4-7 kg sample of d-RDF in a polyethylene bag. Make sure to sample entire width of belt. Immediately seal the bag air-tight.

2.2 Label sample as to sample number, date, time, contents and collection point.

3.0 Test Procedure

3.1 Screen sample (see Fines Content Determination - Method A.5 - Test Procedure).

3.2 Riffle screen overs to approximately 20 pellets. Measure the length of each pellet with calipers and record.

3.3 Re-combine the 20 or so pellets with the remainder of the riffled sample. Repeat step 3.2 twice for total of three riffles.

4.0 Calculations (3)

4.1 Calculate the mean length ($\bar{x}$) of the three riffles combined

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

where:

x_i = individual pellet length

n = total number of pellets of the three riffles.

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METHOD D.7

Drop Shatter Test (Integrity Test)

1.0 Apparatus

1.1 Drop Shatter Box - 61 cm x 30 cm wooden box with two hinged bottom doors 61 cm x 15 cm opening lengthwise and bolt-latched shut. Top side is open. Handles are attached to sides.

1.2 Steel Plate - 122 cm x 61 cm x 0.6 cm with 70 cm high cardboard siding.

1.3 Riffle Sampler - 18 chutes of 2.5 cm width.

1.4 Vernier Calipers - range 1 to 120 mm in 0.1 mm divisions.

2.0 Sample Collection

2.1 As-produced Sample - From discharge of the pellet mill, collect a d-RDF sample of approximately 15-25 kg in moisture-tight container. Label sample as to sample number, date, time, contents and collection point.

2.2 Storage Yard Sample - Collect approximately 45 kg composite sample from location to be tested. Riffle down to a single sample of 15-25 kg. Store in sealed plastic bag and label as to sample number, date, time, contents and collection point.

3.0 Test Procedure

3.1 Riffle the 15-25 kg sample to a portion of approximately 407 kg. Record weight.

3.2 Screen sample at 3/8 inch. Weigh the -3/8 inch material. (See d-RDF Fines Content Determination - Method A.5).

3.3 Riffle screen overs to approximately 20 pellets and measure the length of each pellet with calipers and record. Repeat twice for total of three riffles. (See d-RDF Length Distribution Determination - Method D.6).

3.4 Re-combine screen unders (-3/8 inch material) with screen overs and re-combine this 4-7 kg portion with 15-25 kg gross sample.

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3.5 Place sample in drop box and raise box so its bottom is six feet above steel plate. Allow sample to fall by releasing bolt latch. Repeat this step.

3.6 Repeat screening and measuring 3.1 - 3.3 on dropped sample.

4.0 Calculations (4)

4.1 Calculate the mean length of the three combined before-drop riffles.

$$\overline{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

where:

$\overline{x}$ = mean pellet length
x_i = individual pellet length
n = total number of pellets in combined three riffles

4.2 Calculate the variance of the three before-drop riffles combined.

$$s^2 = \frac{\sum_{i=1}^{n} (x_i-\overline{x})^2}{n-1}$$

where:

s^2 = variance

4.3 Repeat 4.1 and 4.2 on dropped pellets data.

4.4 Test the null hypothesis (H_o) that the population variance ($\sigma^2{}_b$) before drop equals the population variance ($\sigma^2{}_a$) after drop ($\sigma^2{}_b = \sigma^2{}_a$) against the hypothesis that the two are not equal ($\sigma^2{}_b \neq \sigma^2{}_a$).

4.4.1 Calculate the variance ratio (F)

$$F_{calc.} = \frac{S^2_h}{S^2_l}$$

where:

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S_h^2 = higher variance of the before and after combined riffles

S_l^2 = lower variance of the before and after combined riffles

4.4.2 In F table, select critical value of F ($F\alpha$) for $\alpha = 0.05$ (95% level of certainty) and degrees of freedom, ν_h and ν_l, where:

ν_h = degrees of freedom of $S_h^2 = (n_h - 1)$

ν_l = degrees of freedom of $S_l^2 = (n_l - 1)$

n_h = number of pellets in combined riffles of S_h^2

n_l = number of pellets in combined riffles of S_h^2

4.4.3 If F calculated $<F_\alpha$, report H_o accepted.
If F calculated $>F_\alpha$, report H_o rejected.

6-1/2"

4.5 Test the null hypothesis (H_o) that population mean (μ_b) before drop equals population mean (μ_a) after drop ($\mu_b \neq \mu_a$) against the alternative hypothesis that the two are not equal ($\mu_b \neq \mu_a$).

4.5.1 Calculate the combined standard deviation of the before and after drop riffles (S_p).

$$S_p = \frac{(n_h)\ (S_h^2) + (n_l)\ (S_l^2)}{n_h + n_l}$$

4.5.2 Calculate t

$$t = \frac{\bar{x}_b - \bar{x}_a}{S_p} \qquad \frac{n_b n_a}{n_b + n_a}$$

where:

$\bar{x}_b$ = mean length of combined before-drop riffles

$\bar{x}_a$ = mean length of combined after-drop riffles

n_b = total number of pellets in combined before-drop riffles

n_a = total number of pellets in combined after-drop riffles

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4.5.3 In table of Student's t values, find the t_α value for $\alpha = 0.05$ and ν, where:

$$\nu = (n_b - 1) + (n_a - 1)$$

4.5.4 If t calculated $<t_\alpha$, report H_o accepted. If t calculated $>t_\alpha$, report H_o rejected.

4.6 Test the null hypothesis (H_o) that there is no significant shift in pellet length distribution after drop against the alternative hypothesis that there is a shift.

4.6.1 Tally individual pellet lengths of the three combined before-drop riffles into cells of initially 0-1 mm and of 2.5 mm intervals thereafter. Label this tally the Expected Distribution.

6-1/2"

4.6.2 Repeat 4.6.1 for combined after-drop riffles pellet length data. Label this tally the Observed Distribution.

4.6.3 If number of pellets in any one cell of the Expected Distribution is less than five, combine with as many adjacent cells as necessary for total to equal or exceed five. Treat these combined cells as one cell. Combine the corresponding cells in the Observed Distribution and treat that combination as one cell also.

4.6.4 If total frequency (combined measurements of three riffles) of Observed Distribution (f_o) $\neq$ total frequency (combined measurements of three riffles) of Expected Distribution (f_e), multiply the frequency of each Observed cell by the factor $\frac{f_e}{f_o}$.

Use adjusted cell frequencies in subsequent calculations.

4.6.5 Calculate χ^2 (chi-square)

$$\chi^2_{\text{calc.}} = \sum_{i=1}^{k} \frac{(O_i - E_1)^2}{E_i}$$

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where:

k = number of cells

O_i = number of pellet lengths in Observed cell i

E_i = number of pellet lengths in Expected cell i

4.6.6 In table of χ^2 values, find the critical value of χ^2 (χ^2_α) for $\alpha = 0.05$ and $\nu = (k-1)$.

ν = degrees of freedom.

4.6.7 If χ^2 calculated $<\chi^2_\alpha$, report H_o accepted.

If χ^2 calculated $>\chi^2_\alpha$, report H_o rejected.

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APPENDIX E

PLOTS OF DISTRIBUTIONS OF d-RDF PROPERTIES

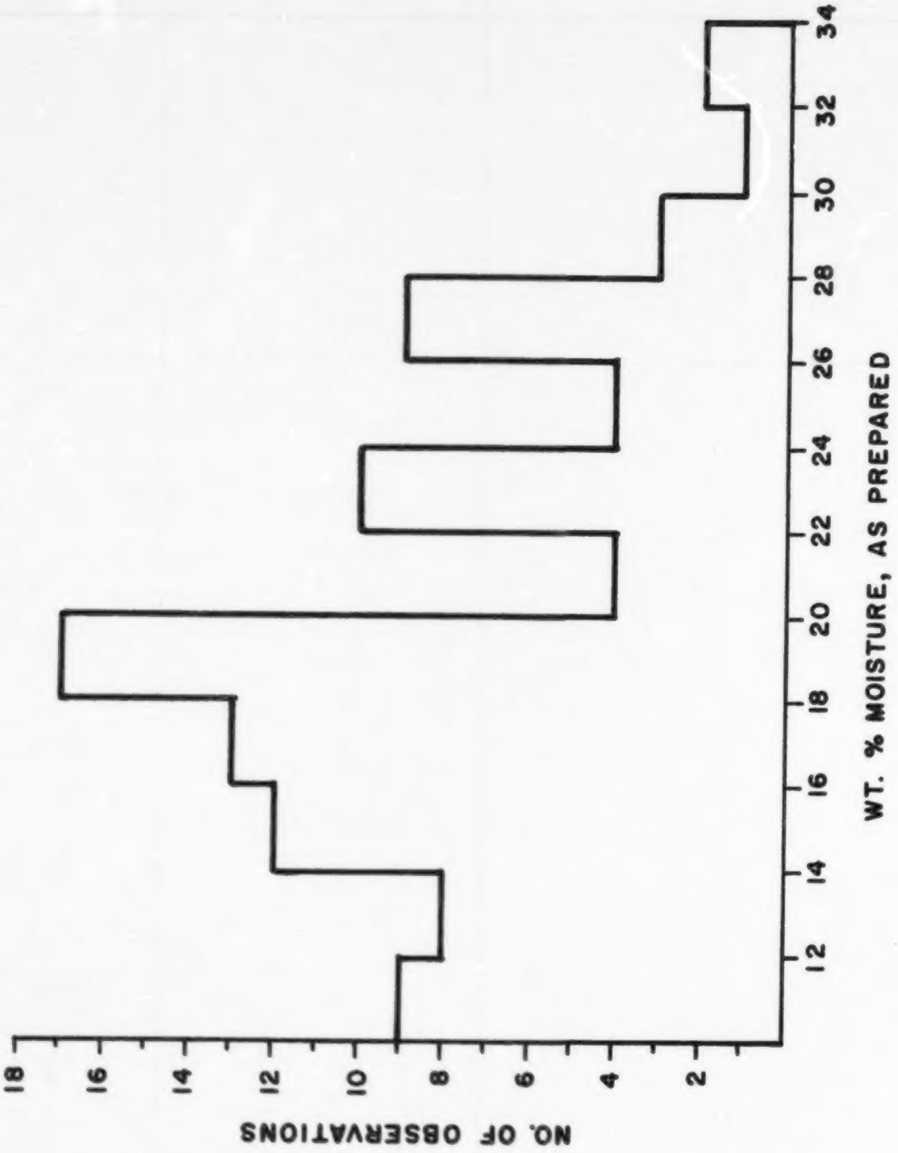

Figure E-1. Distribution of moisture, 92 observations. Moisture contents as prepared before natural drying. x = 19.1%, σ = 5.405.

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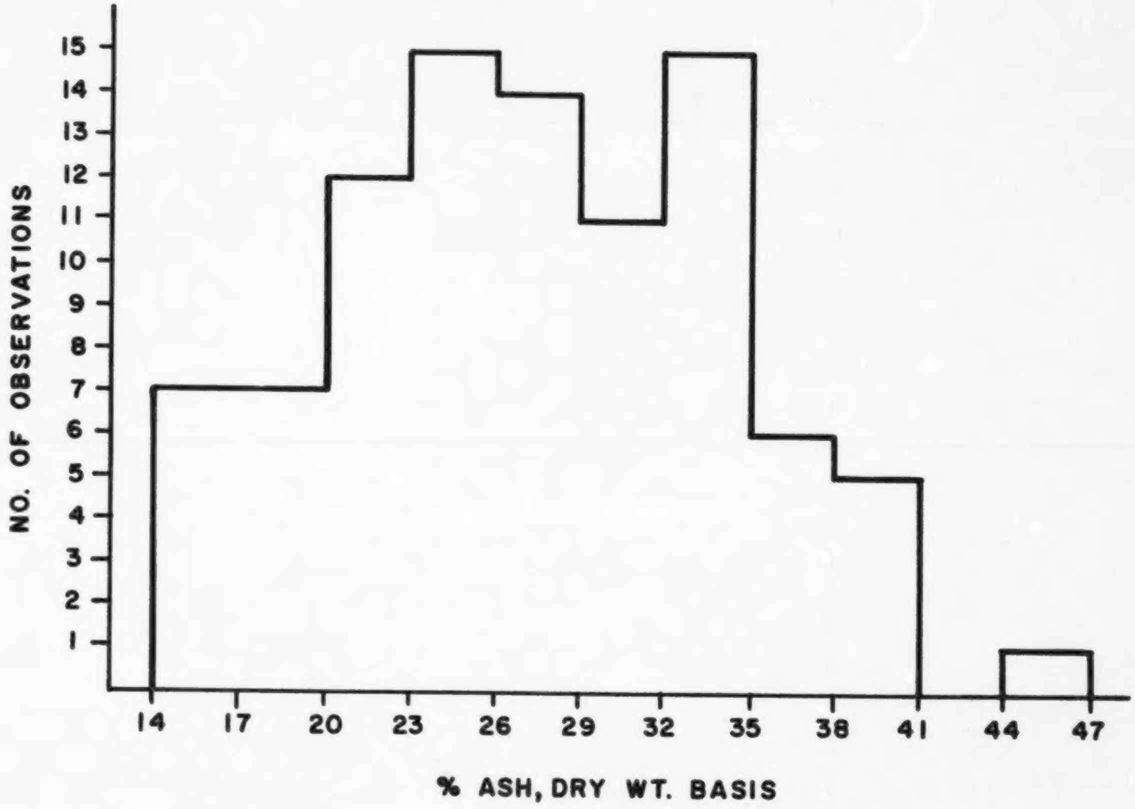

Figure E-2. Distribution of 93 observations of ash content. $\overline{x}$ = 26.55 wt%, σ = 6.268.

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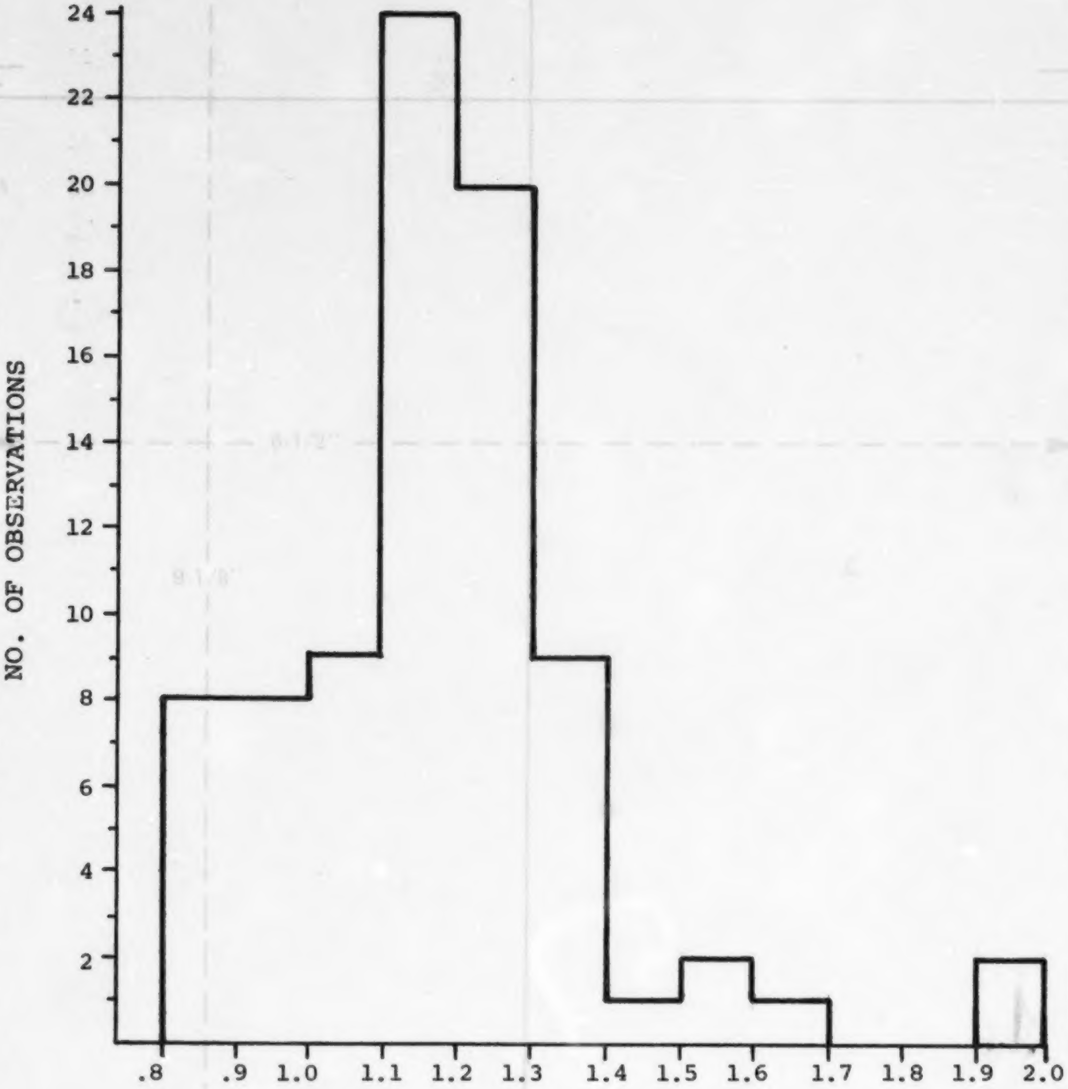

Figure E-3. Distribution of pellet density measurement, 83 observations, each the average of 5 to 7 measurements. $\overline{x}$ = 1.169 Gms/cc, σ = 0.2141.

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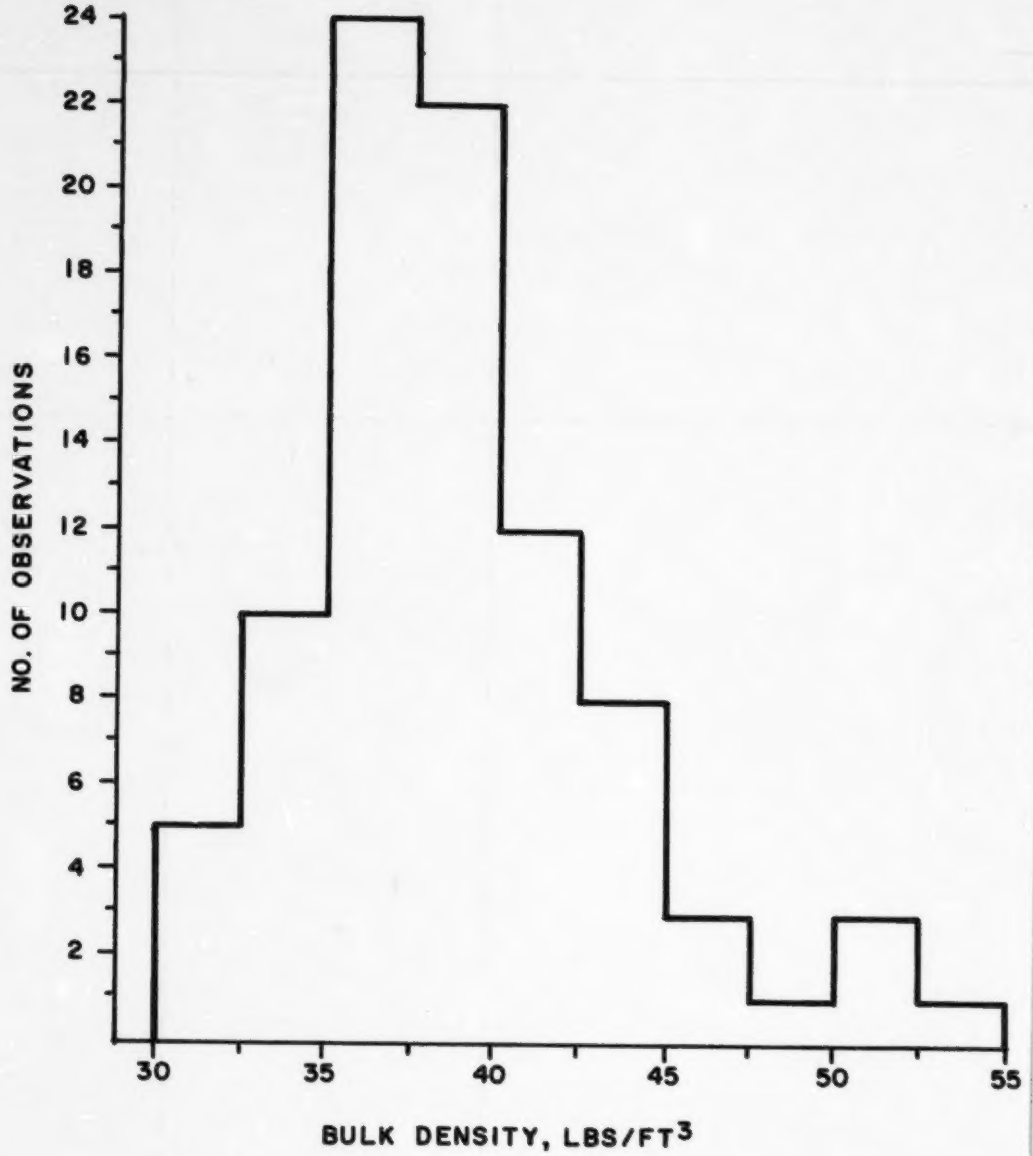

Figure E-4. Distribution of 89 observations of bulk density. $\bar{X} = 38.64$ lbs/ft^3, $\sigma = 4.468$.

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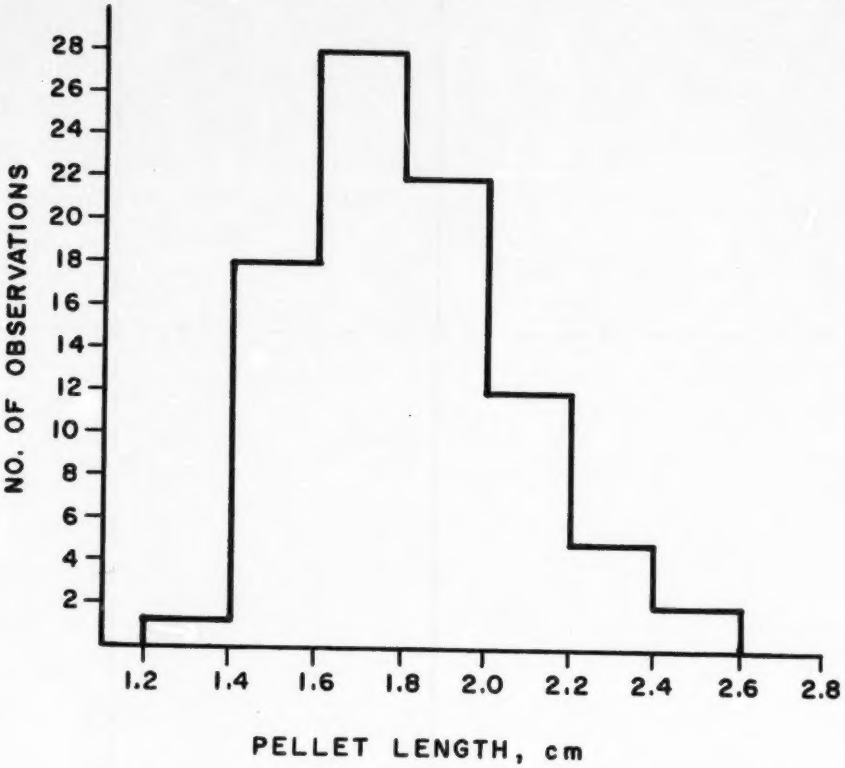

Figure E-5. Distribution of pellet lengths, 88 observations, each the average of 5 to 7 measurements. $\bar{x}$ = 1.794 cm. σ = 0.264.

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APPENDIX F

ESTIMATES FOR d-RDF MODULE CAPITAL AND OPERATING AND MAINTENANCE COSTS

TABLE F-1. d-RDF MODULE CAPITAL COST ESTIMATES (1979 Costs)

Item	1 Densifier	2 Densifiers
Equipment (W = width, L = length)		
Feed conveyor(s) -- 0.7 m W x 9 m L	$ 6,000	$ 12,000
Product conveyor(s) -- 0.5 m W x 10 m L	11,300	16,200
Fines conveyor -- 0.5 m W x 8 m L	4,500	4,500
Surge bin -- 2 m L x 1.5 m W x 3 m L	Included w/densifier	
Densifier w/surge bin, mixer, feeder, rolls	70,000	140,000
2 ea. - 75 cm I.D., 25 mm dies	11,500	23,000
1 ea. - Spare 33 cm rolls	2,800	5,600
1 ea. - 200 hp motor	8,000	16,000
Pellet cooler w/blower	12,900	14,500
Pellet screener -- 18 mm holes	3,100	6,200
Motor control center	3,000	5,000
Equipment subtotal	$133,100	$243,000

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TABLE F-1 (Continued).

Item	1 Densifier	2 Densifiers
Freight and Taxes		
2% Freight and 5% taxes = 7%	$ 9,300	$ 17,000
Installation		
20% Mechanical + 10% electrical = 30% (25% w/2 densifiers)	$ 40,000	$ 65,000
Building Allocation		
45 sq m for 1 densifier	$ 12,000	
75 sq m for 2 densifiers		$ 20,000
Installed subtotal	$194,400	$345,000
Engineering		
8% Installed subtotal	$ 15,600	$ 27,600
Contingency		
5% Installed subtotal	$ 9,700	$ 17,300
Total capital cost	$219,700	$389,900

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TABLE F-2. d-RDF MODULE OPERATING AND MAINTENANCE COST ESTIMATES

(1979 Costs)

Item	1 Densifier	2 Densifiers
Labor (Annual Basis)		
Equipment monitor(s) @ $22,500/yr		
1/2 time for 1 densifier/1 shift	$11,250	
/2 shifts	(22,500)	
2/3 time for 2 densifiers/1 shift		$15,000
/2 shifts		(30,000)
Materials, supplies, tools (Annual Basis)		
$300/month for 1 densifier/1 shift	$ 3,600	
/2 shifts	(7,200)	
$500/month for 1 densifier/1 shift		$ 6,000
/2 shifts		(12,000)
Annual labor & materials - subtotals		
/1 shift	$14,850	$21,000
/2 shifts	(29,700)	(42,000)
Total labor & materials (unit throughput basis)		
For 1 or 2 shifts (7 or 14 hr/day), 3.6 Mg/hr, 250 day/yr	$2.35/Mg ($2.15/ton)	
For 1 or 2 shifts (7 to 14 hr/day), 7.2 Mg/hr, 250 day/yr		$1.67/Mg ($1.53/ton)

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TABLE F-2 (Continued).

Item	1 Densifier	2 Densifiers
Utilities (unit throughput basis - 1 or 2 densifiers)		
1 Densifier module 240 hp @ 60% load = 144 hp; @ 0.745 kW/hp = 108 kw; @ $0.043/kWh and 3.6 Mg/hr = $1.28 Mg		$1.28/Mg
Total utilities		($1.15/ton)
Maintenance (unit throughput basis)		
Densifier dies -- 3200 Mg life		
Cost new die	$5,900	
Cost to regrind (1 time)	300	
Labor	200	
	$6,400	@ 3200 Mg= $2.00/Mg ($1.83/ton)
Densifier rollers -- 1600 Mg life		
Cost new shells (2)	$ 800	
Cost new seals, bearings	1,000	
Labor	250	
	$2,050	@ 1600 Mg = $1.28/Mg ($1.17/ton)
Densifier -- miscellaneous		
Shear pins, lubricants, etc.	$1,000	@ 3200 Mg = $0.31/Mg ($0.29/ton)
Conveyors, cooler, screen		
Labor and material		$0.32/Mg ($0.30/ton)
Total maintenance		$3.91/Mg ($3.59/ton)

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APPENDIX G

REPRESENTATIVE LISTING OF DENSIFICATION EQUIPMENT MANUFACTURERS

California Pellet Mill
1114 E. Wabash Avenue
Crawfordsville, Indiana 47933

Agnew Environmental Products
P. O. Box 1168
Grants Pass, Oregon 97526

Papakube Corp.
1211 Rockhurst Drive
San Diego, California 92120

Ferro-Tech
467 Eureka Road
Wyandotte, Michigan 48192

Sprout-Waldron
Koppers Company, Inc.
Muncy, Pennsylvania 17756

Bühler-Miag
4515 Willard Avenue
Chevy Chase, Maryland 20015

Trans Energy Systems
1605 116th Avenue, N.E.
Bellevue, Washington 98004

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APPENDIX H

FRONT-END CAPITAL COST ESTIMATE - SMALL d-RDF FACILITY - 1979
(Reference Figure 35)

EQUIPMENT DESCRIPTION	COST ESTIMATE
Front End Loader	\$25,000
Receiving Conveyor #1 - 25m x 2m	37,500
Feed Conveyor #2 - 12 m x 2m	18,000
Flail Mill	60,000
Outfeed Conveyor #3 4m x 1m; #4 - 10m x 1m	10,000
Trommel 8 m L x 3m Ø - 38 mm and 203 mm openings	85,000
Overs Conveyor #5 - 3m x 2m	3,000
Residue Conveyors #6 - 18m x 1m; #7 - 6m x 1m #8 - 10m x 1m; #9 - 8m x 1m	30,000
Feed Conveyor #10 - 10m x 1m	7,000
Tramp Mat'l Separator	60,000
Outfeed Conveyors #11 - 3m x 1m, #12 - 9m X 1m	8,500
Magnetic Separator	8,000
Ferrous Conveyor #13 - 8m x.5m	5,000
Secondary Shredder	125,000
Outfeed Conveyor #14 - 3m x 1m	2,500
d-RDF Module - not included here - see Appendix A-1	--
Dust Control System	30,000
Motor Control Center, Operator Panel & Stations	50,000
Miscellaneous Tools/Spares	25,000
Equipment Sub-Total	\$589,500
Taxes & Freight - 7% Equipment	41,300
Installation Mechanical/Electrical - 30% Equipment	176,900
Building - 1680m^2 @ \$360/m^2	600,000
Installed Sub-Total	1,407,000
Engineering @ 10%	140,000
Contingency @ 10%	140,000
Capital Cost Total	\$1,687,700

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